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AFOSR 90 0695 APP. D PT. II

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE
3. REPORT TYPE AND DATES COVERED	Annual
4. TITLE AND SUBTITLE	Laboratory Graduate Fellowship Program Appendix D PT. II
5. FUNDING NUMBERS	61102F ~~2306/D6~~ 3484/D6
6. AUTHOR(S)	Dr. Darrah, Lt. Col Claude Cavender
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	Universal Energy Systems Inc.
8. PERFORMING ORGANIZATION REPORT NUMBER	AFOSR-TR- 90 0695
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	AFOSR/XOT Bld 410 Bolling AFB, D.C. 20332-6448
10. SPONSORING/MONITORING AGENCY REPORT NUMBER	F49620-86-C-0127
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT	Approved for Public Release
12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)	See Attached
14. SUBJECT TERMS	
15. NUMBER OF PAGES	
16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT	Unclassified
18. SECURITY CLASSIFICATION OF THIS PAGE	Unclassified
19. SECURITY CLASSIFICATION OF ABSTRACT	Unclassified
20. LIMITATION OF ABSTRACT	N/A

APPENDIX D PT. II

CERTIFICATIONS AND CONCURRENCE

(CONTINUED)

AFOSR-TR- 90 0695

I. INTRODUCTION

Critical to the success of the Air Force Office of Scientific Research (AFOSR) mission is the ability of AFOSR to draw upon the research community in the United States to respond to its needs. In recent years, however, the number of U. S. citizens seeking advanced degrees in the areas of Air Force research interests has been decreasing. This refers specifically to the number of U. S. citizens obtaining Ph.D. degrees in areas of mathematics and science that are of interest to the Air Force. This situation points toward the potential problem of a future shortage of qualified researchers in areas critical to the nation's security interest.

To address this problem, the United States Air Force Laboratory Graduate Fellowship Program (USAF/LGFP) was established. The contract is funded under the Air Force Systems Command by the AFOSR. The program annually provides three-year fellowships for at least 25 Ph.D. students in research areas of interest to the Air Force. Universal Energy Systems, Inc. (UES) has completed the third year of the three-year LGF program contract.

This report, prepared in compliance with contractual requirements, covers the third year of the program which now sponsors 27 first-year participants as well as 25 second-year fellows and 22 third year fellows for a total of 74 active fellowships. The report addresses an overview of the administration tasks, statistics on the 1989 awards, profiles of all the fellows, and summarized results of the evaluation process. Materials deemed inappropriate for inclusion in the main body of the report, such as samples of forms, complete questionnaire results, etc., are included in the appendices.

II. ADMINISTRATION

The administration of the LGF program is conducted from the Dayton offices of UES. The staff consists of Mr. Rodney C. Darrah, Program Manager; Ms. Judy Conover, Program Administrator; and support personnel. Most members of the 1989 program administration team have been involved with the project since award of the contract to UES. This element of an experienced, stable staff ensures program continuity and contributes to successful operation of administrative tasks.

The primary tasks in managing the program consist of advertising (which includes compiling and updating a mailing list, and preparing and distributing ads, flyers, and

Summary

1. Activation of protein kinase C (PKC) by phorbol esters or diacylglycerols has been shown to modulate a number of ionic currents carried by Ca^{2+}, K^{+}, and Cl^{-}. Recently, it has been demonstrated that PKC may be activated by cis-fatty acids (c-FAs) in the absence of either phospholipid or Ca^{2+}. We wished to determine if this new class of PKC-activating compound would also modulate ionic currents, and if so, to determine the nature of that modulation. To this end, we applied the whole-cell patch clamp recording technique to N1E-115 neuroblastoma cells differentiated in 4% dimethylsulphoxide (DMSO).

2. Analysis of families of currents evoked under voltage clamp by depolarizing steps from a holding potential of -85 mV during application of 5 uM oleate (a c-FA) showed a 36% reduction of the peak inward current with no shift in either the peak or the reversal potential of the current-voltage (I-V) relation and no alteration of outward current.

3. As previous work has shown the inward current of this cell to be largely carried by Na^{+}, we sought to record the isolated Na^{+} current by application of external Mg^{2+}, internal F^{-} and tetraethylammonium (TEA), and the replacement of internal K^{+} with N-methylglucamine. The isolated Na^{+} current recorded in this manner was completely and reversibly abolished by tetrodotoxin or removal of external Na^{+}, and was unaffected by application of external TEA.

CONCURRENCE FORM

The Weapons Laboratory requests the continuation of the AFOSR fellowship for Mr. David A. Taff, studying Scientific Computing at The University of Colorado at Denver.

Give a brief statement of laboratory and/or Mr. Kenneth Summers's (fellow's mentor) involvement with Mr. David A. Taff.

Within the last certification period (April 89 - June 89) and because of internal reorganization, Mr. Taft has been reassigned to me (Capt Ed Carmona). During these last three weeks interaction has been limited to electronic mail. I've learned that Mr Taft is now in the transition of choosing his dissertation topic and is interested in our suggestions. Preliminary discussions for Mr Taft to visit the Lab to discuss efforts in Parallel Computing and possible thesis topics were well received and

Carl Edward Oliver — Chief Scientist — Date

Edward [illegible] 29 Jun 89 — Mentor — Date

CARL EDWARD OLIVER, LT COL, USAF
Deputy Chief Scientist 3 Jul 89

should result in short visit this summer.

S-789-000-022

Atch #2

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David A. Taff

Semester: Spring 1989

University: University of Colorado at Denver

Subcontract: S-789-000-022

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

MATH 5661 NUMERICAL ANALYSIS II B+
MATH 5663 NUMERICAL PARTIAL DIFFERENTIAL EQUATIONS A
MATH 5698 MULTIGRID METHODS FOR PDE I A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Topic to be determined during Summer Semester

"I certify that all information stated is correct and complete."

David A. Taff

Signature/Fellowship Recipient

David A. Taff

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4966C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. David A. Taff is making satisfactory academic progress toward a Ph.D. in the area of Scientific Computing in the discipline of Mathematics for the Spring 1989 semester."

William L. Briggs

Signature/Advising Professor

William Briggs, Associate Professor

TYPED NAME/TITLE OF ADVISING PROFESSOR

4966C

CONCURRENCE FORM

The Weapons Laboratory requests the continuation of the AFOSR fellowship for Mr. David A. Taff, studying Scientific Computing at The University of Colorado at Denver.

Give a brief statement of laboratory and/or Mr. Kenneth Summers's (fellow's mentor) involvement with Mr. David A. Taff.

Mr Taft has visited the laboratory & met with members of the Computational Research Group (WL/SCPS) & with the Deputy Chief Scientist, Lt. Col. C.E. Oliver. On this trip, & through phone conversations, he discussed possible Thesis topics & advisors, as well as the direction of research in parallel computation at the laboratory.

Carl Edward Oliver

Chief Scientist Date

18 Apr 89

Kenneth J. Summers 18 Apr 89

Mentor Date

S-789-000-022

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David A. Taff | Semester: Fall 1988

University: University of Colorado at Denver | Subcontract: S-789-000-022

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

MATH 5660 Numerical Analysis B
MATH 5743 Nonlinear Differential Equations A
Germ 2210 German Reading & Translation A-

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Coursework requirments being completed. Dissertation topic to be determined during summer semester.

"I certify that all information stated is correct and complete."

David A. Taff
Signature/Fellowship Recipient

David A. Taff
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4966C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David J. Ward   Semester: Summer 1989

University: Princeton University   Subcontract: S-789-000-023

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

No courses were offered by the University during the summer.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

The work towards my dissertation has been continuing steadily. I have been modifying the NOVA-W stability code to account for the active feedback terms as well as the passive resistive conductors in the tokamak vacuum region (see description on previous reports). I gave a presentation at the 13th Conference on the Numerical Simulation of Plasmas, Santa Fe, Sept. 17-20. Enclosed is a copy of the four page summary paper printed in the proceedings of this conference. Also enclosed is a reprint of a paper published this summer about work done two years ago.

"I certify that all information stated is correct and complete."

David J. Ward

Signature/Fellowship Recipient

David J. Ward

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4967C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. David J. Ward is making satisfactory academic progress toward a Ph.D. in the area of Plasma Physics in the discipline of Physics for the Summer 1989 semester."

Stephen C. Jardin

Signature/Advising Professor

Stephen C. Jardin, Principal Research Physicist; Professor, Dept. of Astrophysical Sciences.

TYPED NAME/TITLE OF ADVISING PROFESSOR

4967C

MODELLING THE EFFECTS OF THE SAWTOOTH INSTABILITY IN TOKAMAKS USING A CURRENT VISCOSITY TERM

D.J. WARD, S.C. JARDIN
Princeton Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey,
United States of America

ABSTRACT. A new method for modelling the sawtooth instability and other MHD activity in axisymmetric tokamak transport simulations is proposed. A hyper-resistivity (or current viscosity) term is included in the mean field Ohm's law to describe the effects of the three-dimensional fluctuating fields on the evolution of the inverse transform q characterizing the mean fields. This term has the effect of flattening the current profile while dissipating energy and conserving helicity. A fully implicit MHD transport and two-dimensional toroidal equilibrium code has been developed to calculate the evolution in time of the q-profile and the current profile using this new term. The results of this code are compared with the Kadomtsev reconnection model in the circular cylindrical limit.

1. INTRODUCTION

Currently, tokamak transport simulation codes play an active and important role in magnetic fusion research. These codes have proved useful, not as methods for predicting plasma behaviour from first principles but rather as lower dimensional reduced descriptions which enforce the appropriate conservation equations. They also account for fine scale or fluctuating three-dimensional phenomena by means of 'anomalous' coefficients or heuristically motivated prescriptions.

One such class of phenomena which it is essential to model at some level is the sawtooth instability [1]. At present, several approaches are used in doing this. One approach [2] is to incorporate the Kadomtsev complete reconnection model [3] at time intervals which are either predetermined or linked in some way with the plasma evolution. Another method [4–7] used is to modify the electrical resistivity profile in the interior of the magnetic surface defined by the q = 1 surface.

Each of these prescriptions has some merit, but each also has some inconsistencies. The Kadomtsev model is only strictly applicable to a cylindrical plasma of circular cross-section in which a pure helical mode can exist. Even then, there is no guarantee that the helical structure would fully reconnect as assumed by this model. In addition, the Kadomtsev reconnection model is generally believed to give crash times that are too long [8, 9]. The electrical resistivity modification model does not explicitly conserve magnetic helicity as would be done by the underlying MHD instability.

This paper deals with a new method for modelling the effects of the sawtooth instability in a tokamak transport code, based on introducing a 'hyper-resistivity' or current viscosity term in the transport equations. It has been shown by several authors [10–13] that the effects of 3-D MHD fluctuations on the force-free mean field of a plasma can be represented by the introduction of a new term with one free parameter into Ohm's law such that

$$\vec{E} + \vec{v} \times \vec{B} = \eta_{\parallel}\vec{J}_{\parallel} + \eta_{\perp}\vec{J}_{\perp} - \frac{\vec{B}}{B^2}\,\nabla\cdot\left\{\left[\lambda\nabla\left(\frac{\vec{J}\cdot\vec{B}}{B^2}\right)\right] - \left[\vec{u}\times\nabla\left(\frac{\vec{J}\cdot\vec{B}}{B^2}\right)\right]\right\} \tag{1}$$

where λ is an arbitrary, positive function of position and $\vec{u}$ is an arbitrary vector function of position that may be chosen according to mathematical convenience. The form of the function λ has been calculated explicitly for tearing modes in the reversed field pinch (RFP) [14–16] where hyper-resistivity is shown [14, 17] to sustain the magnetic field reversal and to produce plasmas near the force-free Taylor state [18]. Here, however, we make use only of the fact that an arbitrary, positive λ follows from the derivation in Ref. [13].

The new term conserves magnetic helicity. Equation (1) is, in fact, the unique form of a force-free mean field Ohm's law, under the following assumptions [13]: (1) The exact magnetic field energy and helicity are closely approximated by the energy and helicity of the mean field; (2) the fluctuating field can cause differential transport of both the field energy and the field helicity; and (3) the fluctuating field can lead to enhanced dissipation of field energy but not field helicity. The underlying physical instabilities leading to sawtooth oscillations should satisfy these assumptions; therefore we propose to model sawteeth and other 3-D MHD phenomena using this equation in an MHD transport model.

2. THEORY

It can be shown [19] that in a toroidal system with nested magnetic surfaces the q-profile (safety factor profile) develops in time according to

$$\frac{\partial}{\partial t} q^{-1} = \frac{d}{d\Phi} V_L \tag{2}$$

where Φ is the toroidal flux contained inside the Φ = constant surface, and $V_L(\Phi)$ is the loop voltage, defined by

$$V_L = \frac{2\pi \langle \mathcal{J}\vec{B}\cdot\vec{R}\rangle}{\langle \mathcal{J}\vec{B}\cdot\nabla\phi\rangle}$$

Angle brackets denote the flux surface average, defined by

$$\langle a\rangle = \frac{1}{2\pi}\int_0^{2\pi} a\, d\theta$$

Here, $\vec{R}$ represents the right-hand side of Eq. (1), which can be written

$$\vec{E} + \vec{v}\times\vec{B} = \vec{R} = \vec{R}_C + \vec{R}_H$$

and the Jacobian $\mathcal{J}$ of the (Φ,θ,ϕ) magnetic flux co-ordinate system is defined by

$$\mathcal{J} = [\nabla\Phi\times\nabla\theta\cdot\nabla\phi]^{-1} \tag{3}$$

Here, ϕ represents the axisymmetric toroidal angle, with $|\nabla\phi|^2 = X^{-2}$, θ is the poloidal angle and (X,ϕ,Z) are conventional cylindrical co-ordinates.

If we first consider only the classical term, $\vec{R}_C = \eta_\parallel \vec{J}_\parallel + \eta_\perp \vec{J}_\perp$, the loop voltage appearing in Eq. (2) is

$$V_L^{class} = 2\pi\eta_\parallel \frac{\langle \mathcal{J}\vec{J}\cdot\vec{B}\rangle}{\langle \mathcal{J}\vec{B}\cdot\nabla\phi\rangle}$$

$$= \frac{2\pi\eta_\parallel (g(\Phi))^2}{\mu_0}\frac{d}{d\Phi}\left(\frac{\left\langle |\nabla\Phi|^2 \frac{\mathcal{J}}{X^2}\right\rangle}{g(\Phi)} q^{-1}\right) \tag{4}$$

We have taken the axisymmetric (or mean) magnetic field to be represented in the usual way,

$$\vec{B} = \nabla\phi\times\nabla\Psi + g(\Phi)\nabla\phi \tag{5}$$

with Ψ being the poloidal magnetic flux per radian, $\nabla\Psi = (2\pi q)^{-1}\nabla\Phi$, and g the toroidal field function, $g(\Phi) = [2\pi\langle \mathcal{J}/X^2\rangle]^{-1}$.

Next, consider the new term in the mean field Ohm's law that describes the effects of the 3-D turbulent field. The hyper-resistivity term is

$$\vec{R}_H = -\frac{\vec{B}}{B^2}\nabla\cdot[(\lambda\nabla\sigma) - (\vec{u}\times\nabla\sigma)] \tag{6}$$

where

$$\sigma = \frac{\vec{J}\cdot\vec{B}}{B^2} = \frac{g^2(\Phi)}{\mu_0 B^2 \mathcal{J}}\left\{\frac{\partial}{\partial\Phi}\left[\frac{\mathcal{J}|\nabla\Phi|^2}{X^2}\frac{1}{g(\Phi)}\Psi'\right]\right.$$

$$\left. + \frac{\partial}{\partial\theta}\left[\frac{\mathcal{J}(\nabla\theta\cdot\nabla\Phi)}{X^2}\frac{1}{g(\Phi)}\Psi'\right]\right\} \tag{7}$$

the prime denoting differentiation with respect to Φ.

We take advantage of the fact that $\vec{u}$ can be any arbitrary function of position and specify the form for $\vec{u}$ such that the terms with theta derivatives of σ in Eq. (6) cancel, thus

$$\vec{u} = -\lambda\mathcal{J}(\nabla\Phi\cdot\nabla\theta)\nabla\phi \tag{8}$$

The loop voltage corresponding to the hyper-resistivity term, Eq. (6), then becomes

$$V_L^H = 2\pi\frac{\langle \mathcal{J}\vec{B}\cdot\vec{R}_H\rangle}{\langle \mathcal{J}\vec{B}\cdot\nabla\phi\rangle}$$

$$= -(2\pi)^2\frac{\partial}{\partial\Phi}\left\langle \lambda\mathcal{J}|\nabla\Phi|^2\frac{\partial\sigma}{\partial\Phi}\right\rangle \tag{9}$$

Considerable simplification can be obtained by restricting the form of λ, the arbitrary function of position appearing in Eq. (1), to be of the form

$$\lambda = \frac{\Lambda(\Phi)}{(2\pi)^2 \mathcal{J} |\nabla\Phi|^2} \tag{10}$$

where $\Lambda(\Phi)$ is an arbitrary function of toroidal flux. In addition, we choose the angle θ in the (Φ,θ,ϕ) flux coordinate system so that the Jacobian $\mathcal{J}$ is given by the Boozer form [20]

$$\mathcal{J} = \frac{f(\Phi)}{\mu_0 B^2}$$

where

$$f(\Phi) \equiv \frac{\mu_0}{(2\pi)^2 \langle B^{-2}\rangle} \frac{dV}{d\Phi}$$

$V(\Phi)$ being the volume enclosed by the flux surface with label Φ.

Including the loop voltage due to the classical term, Eq. (4), and that due to the hyper-resistivity term, Eq. (9), in the time evolution equation for q, Eq. (2), gives the final form for the complete equation to advance q in time relative to surfaces of constant toroidal flux

$$\frac{\partial}{\partial t} q^{-1} = \frac{d}{d\Phi}\left[\frac{2\pi\eta_\parallel(\Phi)}{\mu_0}(g(\Phi))^2 \times \frac{d}{d\Phi}\left(\frac{\left\langle|\nabla\Phi|^2 \frac{\mathcal{J}}{X^2}\right\rangle}{g(\Phi)} q^{-1}\right)\right] - \frac{d^2}{d\Phi^2}\left\{\Lambda(\Phi) \times \frac{d}{d\Phi}\left[\frac{g^2(\Phi)}{f(\Phi)}\frac{d}{d\Phi}\left(\frac{\left\langle|\nabla\Phi|^2 \frac{\mathcal{J}}{X^2}\right\rangle}{g(\Phi)} q^{-1}\right)\right]\right\} \tag{11}$$

Equation (11) includes classical resistive field diffusion, as well as the new term representing the effect of the 3-D turbulent fields. We model sawteeth with this equation by evolving the q-profile in time with the resistive term only. When some threshold is reached (e.g., q_0 reaches some critical value), we 'trigger' the sawtooth by turning on the hyper-resistivity term within some inner radius of the cross-section.

As a first test of this model we consider the large aspect ratio cylindrical tokamak limit. The evolution equation, Eq. (11), becomes the simpler 1-D equation:

$$\frac{\partial\Psi}{\partial t} = \frac{\eta(r)}{\mu_0}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Psi}{\partial r}\right) - \frac{1}{r}\frac{\partial}{\partial r}(\bar{\lambda}r)\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r} r\frac{\partial\Psi}{\partial r}\right] \tag{12}$$

where $\bar{\lambda}$ is an arbitrary scalar function closely related to our function $\Lambda(\Phi)$ of Eq. (11), and Ψ is the poloidal flux. In this 1-D version we can compare our model with the Kadomtsev flux reconnection model [3].

3. NUMERICAL METHOD

We have developed a fully implicit code to implement our model in both 1-D and 2-D versions. In the 1-D version we advance the poloidal flux Ψ in time by solving Eq. (12). We normalize the equation to the resistive time. The value of the safety factor q can be found from the spatial derivative of Ψ and the current density by differentiating once again. We solve Eq. (12) by using an implicit finite difference technique and reduce the equations to block tridiagonal form. We integrate Ψ from the boundary inwards with the boundary condition that the spatial derivative of Ψ is constant at the edge. This corresponds to the condition of keeping the total integrated plasma current constant.

In the 1-D case we compare this model with the Kadomtsev reconnection. To calculate the Kadomtsev reconnection we let the poloidal flux evolve owing to resistive relaxation using Eq. (12) with $\bar{\lambda} = 0$. We convert to $m = 1$, $n = 1$ helical flux by subtracting the toroidal flux from the poloidal flux and then use the reconnection formulas given by Kadomtsev [3] to calculate the helical flux after reconnection. We then compare this with the effect of triggering the sawtooth by letting $\bar{\lambda}$ be non-zero in Eq. (12).

In the 2-D version we advance the inverse q by solving Eq. (11) directly. We obtain the metric coefficients that appear in Eq. (11) by merging the transport program with a 2-D MHD equilibrium program [21] that solves for the equilibrium, given the q-profile, at every iteration. The parallel current density ($j_\parallel/B$ averaged over the flux surface) is then found from Eq. (7). The implicit finite differencing technique is similar to that used in the 1-D case with the boundary condition

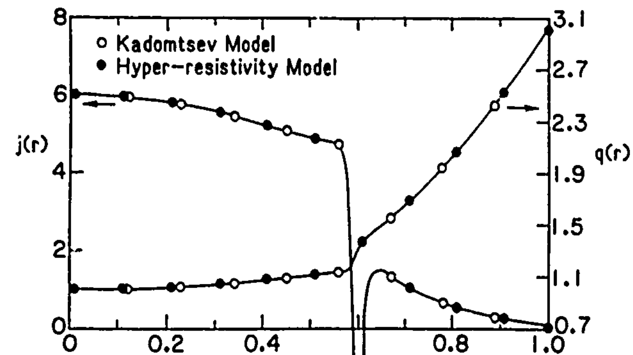

FIG. 1. Current profiles and q-profiles for the Kadomtsev model and for the hyper-resistivity model in the cylindrical limit.

being q(edge) = constant. We again normalize the equation to the resistive time using the total toroidal flux divided by the toroidal field at the plasma edge as the characteristic square length.

To model sawteeth we begin with some initial q-profile, with $q_0 \approx 1$ and q(r) increasing parabolically to the value at the outer radius, q(edge). We let the current profile relax owing to classical resistivity by solving Eqs (11) or (12) with the hyper-resistivity term equal to zero. When q_0 reaches a predetermined threshold, e.g. $q_0 = 0.9$, we allow the hyper-resistivity term to come on by changing λ to a preselected non-zero form. The hyper-resistivity term will have the effect of flattening the current profile and the q-profile in the region where λ is non-zero. When the value of q_0 reaches $q_0 = 1.0$, we set the hyper-resistivity term back to zero and allow the profiles to again relax owing to classical resistivity only. We then repeat the entire process several times until a steady state sawtooth cycle is reached.

4. RESULTS AND DISCUSSION

In our 1-D cylindrical model we have found a form of the arbitrary functional coefficient λ with which our model very nearly matches the results of the Kadomtsev flux reconnection model. We use a classical resistivity profile, given by $\eta(r) = \eta_0 \exp(4.5r^2)$, corresponding to a resistivity that goes like $T^{-3/2}$ where the temperature profile is Gaussian. In addition, we can add neoclassical corrections to the resistivity and examine their effect on the profiles and the time evolution. The hyper-resistivity profile is given by

$$\bar{\lambda}(r) = \begin{cases} \lambda_0 \left(1 - \dfrac{r}{r_s}\right)^{\alpha} & \text{for } r \leq r_s \\ 0 & \text{for } r > r_s \end{cases}$$

The value we use for λ_0/η_0 is 200, and α is equal to 1.20. The value for r_s is determined by finding the point where the 1/1 helical flux is equal to the 1/1 helical flux at the centre. It is inside this point where the Kadomtsev reconnection takes place and where the hyper-resistivity affects the flux. Outside of this point the flux is unchanged by both this model and the Kadomtsev model. Figure 1 shows the current profiles and q-profiles for both models immediately after triggering the sawtooth. Figure 2 shows how q_0 evolves in time according to both models. We see that for this form of $\lambda(\psi)$ the results of this model are nearly identical with those of the Kadomtsev model.

We can visualize how the current profile is affected by the hyper-resistivity as in Fig. 1. From the form of the Ohm's law, Eq. (1), we see that if the magnitude of λ is large enough, then the hyper-resistivity term dominates the right-hand side of the equation. Furthermore, if λ is large, then the gradient of $j_\parallel/B$ must become small in order for the right-hand side of Eq. (1) to balance with the left-hand side. In other words, $j_\parallel/B$ becomes nearly uniform in the region where $\lambda(\psi)$ is large. Larger magnitudes of λ will produce more uniform profiles of $j_\parallel/B$. Just outside the region where the current profile is flattened, we see a sharp current reversal. This corresponds to the region where λ goes to zero. This negative current spike is a result of the inductive effect of the sudden mixing and equalizing of currents on adjacent magnetic surfaces [22]. In the region outside the current reversal the hyper-resistivity term is zero and has no effect on the

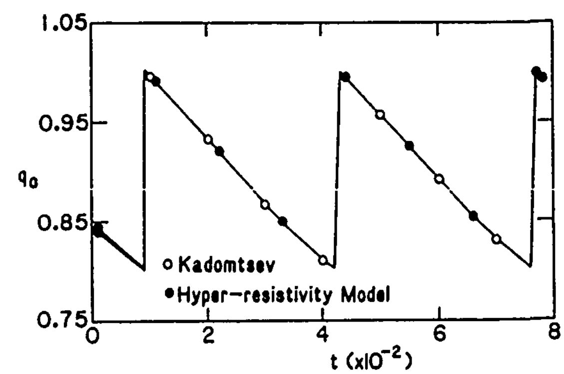

FIG. 2. Time evolution of q on axis, q_0, for both models.

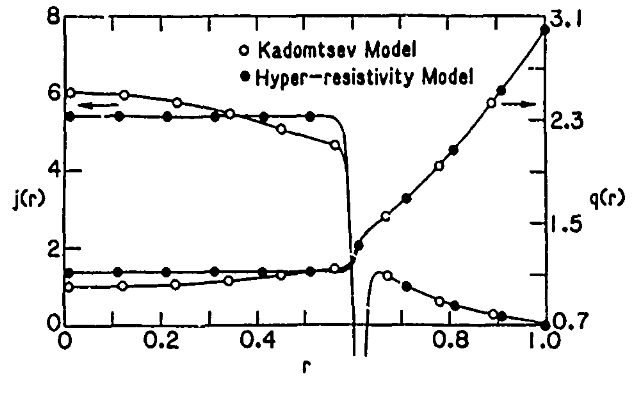

FIG. 3. Current profiles and q-profiles for the Kadomtsev model and for the hyper-resistivity model, with a large value of λ, which gives complete flattening.

equation. The profile is affected here only by classical resistivity; therefore, the current profile in this region is essentially the same as it was before the sawtooth.

By choosing different magnitudes and functional forms for λ we can model sawteeth that are quite different in their precise form, but with the same qualitative behaviour as the Kadomtsev sawteeth. The Kadomtsev model can thus be thought of as one specific case of a more general range of sawtooth behaviour which can be represented by our model. For instance, by changing the position of the λ cut-off, we can change the position of the current reversal and, therefore, determine how much of the inner region of the current profile is flattened. By changing the magnitude of λ we can specify how flat the resulting profile will be. If the magnitude is large enough, we can achieve a complete flattening of the current profile within this inner region. This is shown in Fig. 3. Once this limit in magnitude is reached, any further increase in magnitude or change in the functional form of λ will have no noticeable effect on the resulting profiles.

Figure 4 shows for both the Kadomtsev model and the hyper-resistivity model how the poloidal flux at the centre, Ψ_0, evolves owing to the effect of the sawteeth, with λ equal to that used in Fig. 1. This illustrates how the volt-seconds from the Ohmic coils are 'consumed' by the sawteeth in both models. The effect of sawteeth on volt-second consumption is of considerable importance to the operation of tokamaks during the current flat-top phase, especially for long-pulse reactors [5].

The above mentioned functional forms of the hyper-resistivity are all such that λ goes to zero exactly at some point and remains zero for all larger radii, i.e. these forms have a discontinuous derivative at that point. Such a form is particularly well suited to match the Kadomtsev model, but may not be a good physical description of the hyper-resistivity. We can use forms of λ that are continuous in all derivatives as the function goes to zero, and produce qualitatively similar results as long as the hyper-resistivity approaches zero fast enough with increasing radius. For example, forms such as $\lambda(r) = \lambda_0 \exp(-\alpha r^p)$ will produce behaviour similar to the functional forms used above. The resulting current profile is not as flat and the current reversal is not nearly as sharp as in the Kadomtsev matching case, but the basic features are the same. Therefore, we know that it is not the discontinuity in λ or its derivatives that determines the overall form of the profiles. Again, we have the freedom to change λ_0, α and p in order to alter the precise form of the sawtooth behaviour.

We extend our model to toroidal plasmas with cross-sectional shaping by using our fully 2-D model. We use a form for λ that corresponds to that which we used to match the Kadomtsev model in our 1-D version. This is, therefore, a 2-D ($\beta = 0$) extension of the Kadomtsev prescription to a toroidal plasma with a shaped cross-section. We have run cases for plasmas with circular cross-sections and compared the results with those for plasmas with highly shaped cross-sections in order to see the effect of cross-sectional shaping on sawtooth behaviour.

We consider two cases for our 2-D model: (a) a circular cross-sectional plasma and (b) a plasma with a strongly shaped cross-section (elongation = 1.8 and triangularity = 0.30). Figure 5 shows the current density profiles (j_t/B profiles) and the q-profiles for both

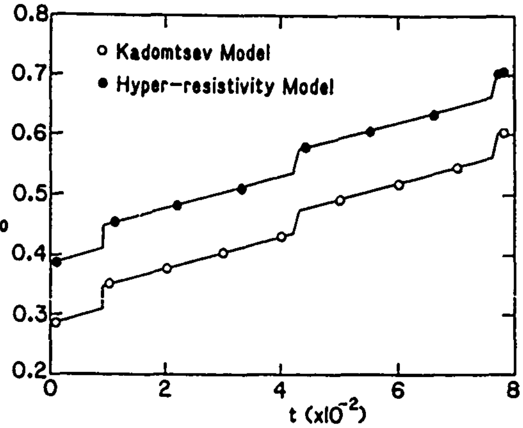

FIG. 4. Time evolution of the poloidal flux on axis, Ψ_0, for both models. Note that the curve for the Kadomtsev model has been displaced downwards, otherwise it would lie directly on top of the other curve.

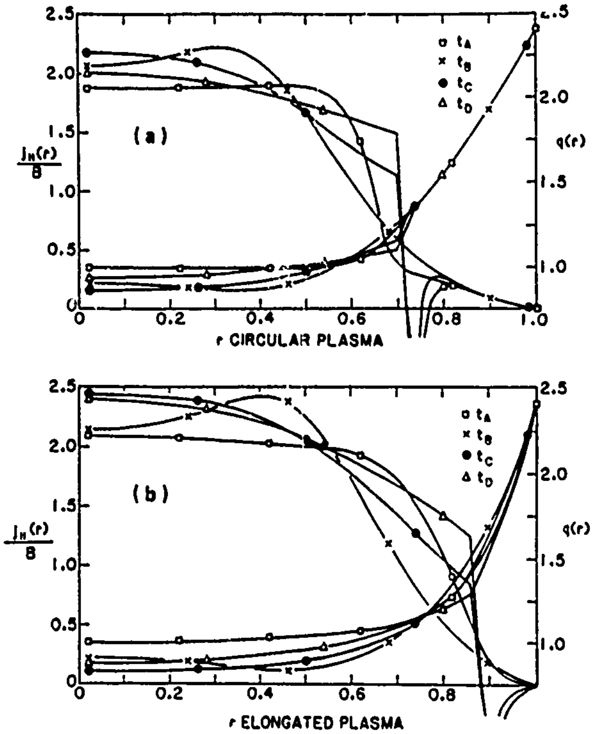

FIG. 5. Current profiles and q-profiles at four different times during the sawtooth cycle for the 2-D model where we have (a) a circular plasma and (b) a highly shaped plasma (elongation = 1.8, triangularity = 0.30). The four times are shown on the time evolution of q_0 in Fig. 7. The radial variable r is the square root of toroidal flux contained within the surface, normalized to the value at the plasma edge.

cases at four times: at two times during the sawtooth crash, shortly after the sawtooth crash ($q_0 \approx 1.0$), and after some resistive relaxation and shortly before triggering the next sawtooth ($q_0 \approx 0.91$). The current profile of the elongated plasma evolves into a more hollow profile, with the value on axis being significantly less than that at the peak. In fact, the value of the current on axis is higher during the first part of the sawtooth crash than it is just before the crash. This effect is much more pronounced for the elongated plasma than it is for the case with the circular cross-section. To illustrate this, we have plotted the value of the current on axis, $j_\parallel(0)/B$, versus time in Fig. 6. We see that there is a significant difference in the development of $j_\parallel(0)/B$ between the circular plasma and the elongated plasma. Figure 7 shows the corresponding time evolution of q_0.

When the plasma recovers from a sawtooth crash, it begins with a fairly flat current profile. The large extent of the sawtooth has redistributed the current over a large portion of the cross-section. As the current diffuses inwards it moves faster where the resistivity profile is steepest. Therefore, the current closer to the edge diffuses inwards fastest and thus the current forms a peak off axis resulting in a slightly hollow current profile. This peak moves towards the axis as the classical resistive diffusion continues. As the current peak gradually diffuses towards the axis it becomes more peaked and therefore the profile becomes more hollow. If this classical resistive diffusion continued indefinitely, the profile would, of course, evolve into its completely relaxed state, but the next sawtooth is triggered (at $q_0 \approx 0.90$) while the profile is still quite hollow. As the sawtooth is triggered, the hyper-resistivity flattens the current profile, and the current density near the axis is larger than that before the sawtooth when there was a local minimum on axis because of the hollow current profile. Therefore, the sawtooth causes a sudden, noticeable jump in $j_\parallel(0)/B$. There is a corresponding drop in q_0. As the hyper-resistivity continues to flatten the current profile, some of the current is redistributed towards the edge and the value of $j_\parallel(0)/B$ falls to the value it takes at the end of the crash. When the hyper-resistivity goes to zero at the end of the sawtooth crash, we have a nearly uniform current profile, and the whole process repeats itself. Keeping these steps in mind, we can

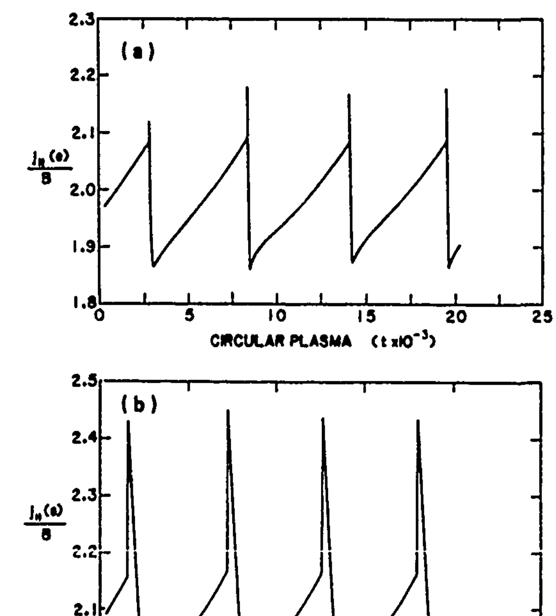

FIG. 6. Time evolution of the current density on axis, $j_\parallel(0)/B$, for (a) the circular plasma and (b) the highly shaped plasma.

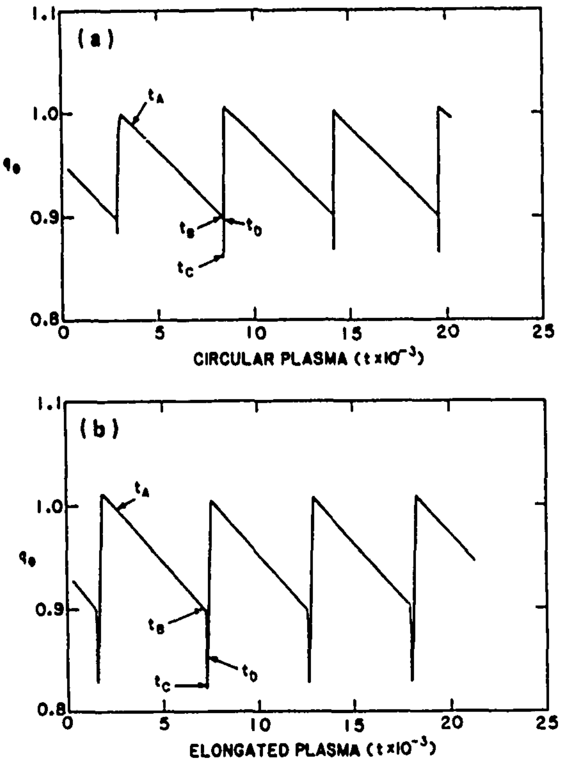

FIG. 7. Time evolution of the value of the safety factor on axis, q_0, for (a) the circular plasma and (b) the highly shaped plasma.

understand the evolution of $j_t(0)/B$ in time, as shown in Fig. 6(b). Furthermore, we can use the same reasoning to see why the evolution of $j_t(0)/B$ in the case of the circular plasma, Fig. 6(a), looks so different.

The evolution of $j_t(0)/B$ in the case of the circular plasma is not nearly so dramatic. Since the current redistribution took place over a smaller region of the cross-section, the off-axis peak is not as pronounced as in the non-circular case. The resulting profiles are therefore not as hollow. The current profile at the time when the sawtooth is triggered (see Fig. 5(a)) is not nearly as hollow as in the case of the highly shaped plasma. Therefore, when the hyper-resistivity begins to flatten the current profile, $j_t(0)/B$ experiences only a small jump and then immediately drops as the current density becomes more uniform across the profile. After the crash, the current diffuses back towards the centre owing to classical resistivity, and $j_t(0)/B$ increases again. Then the sawtooth is triggered again, and the whole process repeats itself. This gives a more conventional sawtooth pattern of $j_t(0)/B$ for the circular plasma.

Figure 8 shows how the helicity, the poloidal flux and the total toroidal flux vary with time. We see that both the absolute and the relative change in poloidal flux are substantially greater in the non-circular case (Fig. 8(b)) than in the circular case (Fig. 8(a)), even for the same relative change in q_0 during the sawtooth. The nearly discontinuous behaviour of the poloidal flux in Figs 8(a), (b) is to be contrasted with the more gradual oscillations in the magnetic helicity,

$$K = \int_0^{\Phi_\ell} (\Psi - \Psi_\ell) d\Phi$$

where the subscript ℓ denotes the value at the limiter or at the plasma edge. The helicity does not change discontinuously because of the direct action of the non-zero λ term, but it does decrease owing to the sharp current spikes created by the action of the sawtooth model. This decrease is compensated for, on the average, by the continued influx of helicity across the plasma boundary. The large current spikes are very near the edge in the non-circular case, and therefore we see larger oscillations in helicity as compared to the circular case.

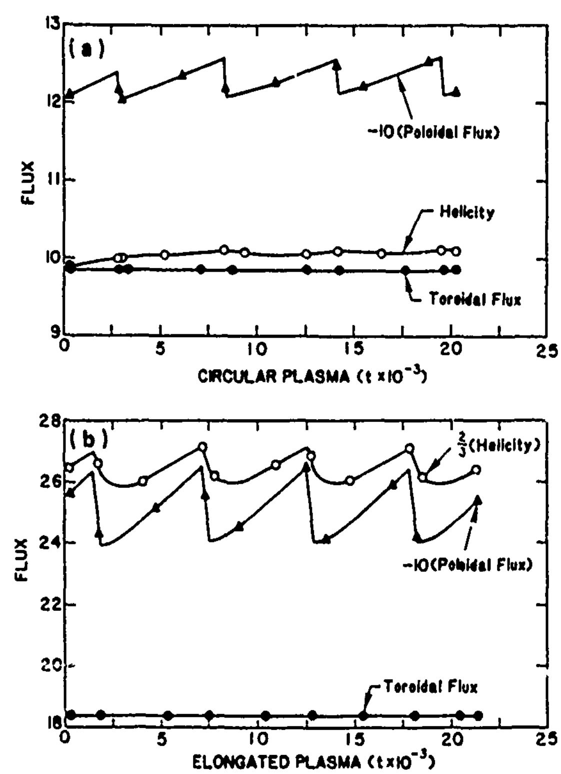

FIG. 8. Time evolution of the helicity, the poloidal flux (ten times the difference between the value at the limiter and the value on axis) and the total toroidal flux, for (a) the circular plasma and (b) the highly shaped plasma.

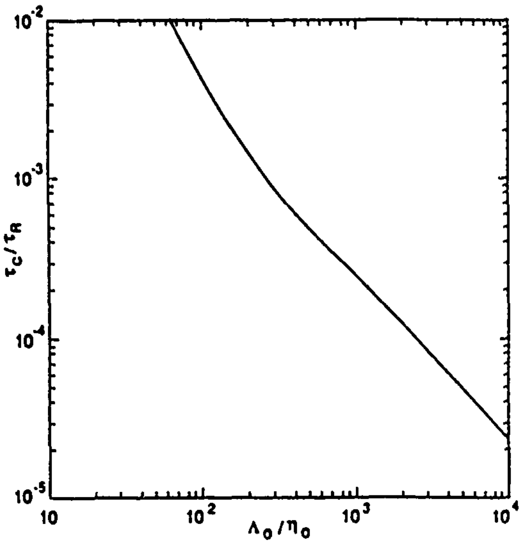

FIG. 9. Sawtooth crash times (normalized to the resistive time, τ_c/τ_R) plotted as a function of the hyper-resistivity magnitude, Λ_0/η_0.

It is clear that all effects of the sawtooth oscillation are more pronounced in the non-circular cross-sectional geometry than in the circular cross-section, although this result clearly depends on the assumption used here that the values of q_0 for which the sawtooth is triggered on and off are independent of the cross-sectional shape. The dominant effect of shaping the cross-section is that for the same value of q at the limiter, the radius over which the current rearrangement occurs is substantially larger for the non-circular case than for the circular case. This is evident from comparing Figs 5(a) and 5(b).

For cases with a larger value of q at the limiter, q(edge), the sawtooth affects a smaller region of the profile. This results in more conventional sawtooth patterns for q_0 and $j_t(0)/B$, even for cases with highly shaped cross-sections. Here, however, we have considered a case with low q(edge) (= 2.41) to demonstrate the strong effects of cross-sectional shaping on the sawtooth behaviour.

The magnitude Λ of the hyper-resistivity primarily determines how fast the current profile is flattened. Therefore, the sawtooth crash time is a function of Λ in our model. The results of a study of the sawtooth crash time variation with the hyper-resistivity magnitude Λ_0/η_0 are shown in Fig. 9. This figure thus defines a 'hyper-resistivity time-scale'. It can be seen that the model produces sawtooth crash times over a broad range. Very slow Kadomtsev-like sawteeth are found with sufficiently low Λ_0/η_0; on the other hand, 'fast-crash' sawteeth can just as easily be produced with larger values of the hyper-resistivity magnitude. This is another demonstration of the versatility of this model.

We have also modified the standard classical resistivity term to include neoclassical corrections. The resulting current profiles develop a characteristic peak at the magnetic axis and a plateau region. Park has derived an analytic expression [23] that describes how q_0 evolves in time owing to neoclassical resistive diffusion:

$$q_0(t) \approx 1 - 2\sqrt{\epsilon_r}\left(\frac{t}{\tau_R}\right)^{1/4} \tag{13}$$

where ϵ_r is the inverse aspect ratio at the inversion radius and τ_R is the resistive time. We trigger our sawteeth at $q_0 = 0.8$ and compare the resulting sawtooth period with that predicted by Eq. (13) for this value of q_0. The line in Fig. 10 depicts the ϵ^{-2} scaling of the sawtooth periods predicted by Eq. (13). The points show the periods from the simulation for several values of ϵ, given a fairly flat temperature profile ($T(r) \sim \exp(-0.5r^2)$). The points fit close to the line, thus following the scaling. The lower curve shows how the sawtooth periods scale with ϵ for a more peaked Gaussian temperature profile. The scaling with ϵ is clearly quite different. Thus, we see that

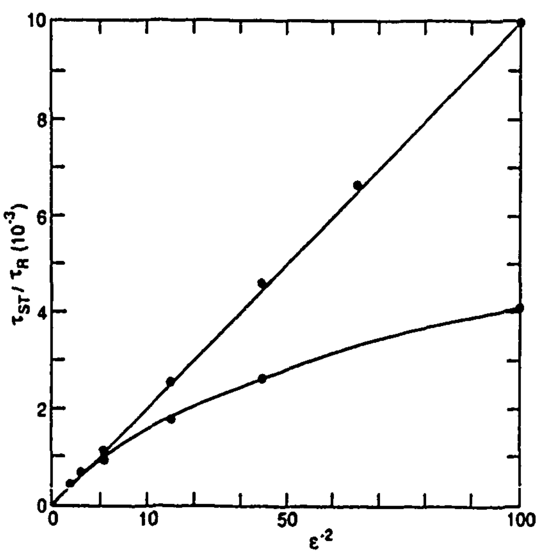

FIG. 10. Sawtooth period scaling with ϵ compared to the scaling predicted by Eq. (13), indicated by the line. The points along the line represent the periods from the simulation at several values of ϵ for a sufficiently flat temperature profile. The lower curve represents the scaling of the sawtooth period with ϵ for a peaked temperature profile.

for a resistivity profile corresponding to a sufficiently flat temperature profile the sawtooth period scales with ϵ as predicted by Eq. (13). Park found that this sawtooth period scaling compares well with experimental Ohmic sawtooth data.

This model can be extended to finite beta plasmas by including an energy transport equation. It has been shown in recent work by Boozer [24] that the thermal conductivity is related to the hyper-resistivity λ and that the electron temperature profile will flatten on a time-scale that is much faster than the flattening of the current profile. Thus the plasma will be effectively force-free in the region where the hyper-resistivity operates. By using such a form for the thermal conductivity in an energy transport model, the evolution of the temperature and pressure profiles could also be modelled. This will be addressed in future work.

Hyper-resistivity has also been used to model tokamak disruptions [25] in order to calculate the effects of disruptions on tokamak vacuum vessel components. Furthermore, we believe that such a term might be used in the modelling of DC helicity injection through induced double tearing modes as in the DC helicity injection scheme on CDX [26]. The form of the hyper-resistivity to be used in the transport code could be derived from calculating the eigenfunction of the double tearing instability using an asymptotic matching code.

5. SUMMARY

We have developed a fully implicit MHD transport code in 1-D and 2-D versions for modelling the effect of the sawtooth instability using a hyper-resistivity term. With the 1-D version we can closely match the results of the Kadomtsev model, by a suitable choice of our parameters determining the form of the hyper-resistivity λ. Given our freedom of this controlling function, we can also model sawteeth with a behaviour different from that of sawteeth in the Kadomtsev model. Thus, the Kadomtsev model may be regarded as a special case of the more general model discussed here. In addition, our model can accommodate a wide range of sawtooth *period* times and sawtooth *crash* times by adjusting the value of Λ_0 and the q_0 trigger value. Furthermore, our model has been extended to (zero beta) plasmas with shaped cross-sections through our 2-D version, so that we can examine the effects of cross-sectional shaping on the profile evolution during sawteeth.

With the 2-D model we have found that plasmas with strong cross-sectional shaping develop hollow current profiles after the sawtooth crash and have a larger fraction of their area affected by the sawteeth. The plasmas that are more strongly shaped develop profiles that are more hollow. The sawtooth crash will initially increase the current density near the axis before current is redistributed outward by the hyper-resistivity. This results in an unusual sawtooth pattern for the current on axis, $j_t(0)/B$.

Our form of hyper-resistivity was chosen to be the form that matched the Kadomtsev model in the cylindrical limit, but it might be possible to develop a more self-consistent model by using a resistive stability code to calculate the eigenmodes and choose the form and magnitude of the controlling function $\lambda(\psi)$ from the results of this stability analysis. The model can also be extended to finite beta plasmas by including an energy transport equation with a thermal conductivity that is related to the hyper-resistivity.

ACKNOWLEDGEMENTS

This work was supported by the United States Department of Energy under Contract No. DE-AC02-76-CHO-3073. One of the authors (DJW) was supported by the United States Air Force under its Laboratory Graduate Fellowship Program.

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(Manuscript received 13 June 1988
Final manuscript received 21 March 1989)

Calculation of Axisymmetric Stability of Tokamak Plasmas with Active and Passive Feedback

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Introduction

It is well known that tokamak plasmas with strong cross-sectional shaping are subject to severe axisymmetric ($n = 0$) instabilities which can destroy the plasma on the ideal MHD time scale. These plasmas can be stabilized on the ideal MHD time scale by placing passive resistive conductors, such as the vessel wall, near the plasma. The plasma is still unstable on the L/R time of the surrounding conductors, but can be totally stabilized over the time of the discharge with an active feedback system.

The efficacy of the active feedback is highly dependent on the details of the active and passive feedback system and the plasma itself. The stabilizing properties of these feedback systems can be analyzed using simplified models that treat the plasma as a collection of filamentary currents, or as having purely rigid motion.[1,2] However, this often is not a good representation because plasmas with strong cross-sectional shaping can have large non-rigid components to their displacements. In fact, it has been shown[3] that plasmas with strong cross-sectional shaping can remain unstable under the effects of a feedback system that would stabilize a plasma with purely rigid motion. The full non-linear motion of a tokamak plasma can be simulated by a time-evolution code such as TSC.[4] While TSC can provide an accurate treatment of both the linear and non-linear axisymmetric motion, it requires an excessive amount of computation to get an accurate converged result. Thus to completely explore the performance of a feedback system using TSC is difficult and expensive. Ideal MHD stability codes such as PEST[5] or ERATO[6] cannot treat non-ideal aspects, such as resistive conductors in the vacuum region or an active feedback system. These codes cannot be simply modified to include these effects since that would destroy the self-adjoint properties of the force operator.

We have developed a *non*-ideal MHD linear stability code, NOVA-W, that calculates the linear stability of the axisymmetric modes with passive and active feedback included. We have modified the vacuum calculation for the NOVA[7] code to include the effects of resistive conductors and feedback currents in the vacuum region. NOVA is a non-variational MHD stability code that directly solves the stability eigenvalue equations without using the δW formulation to calculate stability; therefore, non-ideal effects can be included that would otherwise destroy the self-adjointness property which underlies the δW approach.

Formulation

We are dealing with axisymmetric modes; thus, we can write the perturbed poloidal magnetic field in the vacuum in the flux formulation

$$\vec{b} = \frac{1}{2\pi}\vec{\nabla}\phi \times \vec{\nabla}\chi,$$

where χ is the perturbed flux in the vacuum. We can relate this perturbed flux to the toroidal currents in the vacuum region:

$$X\vec{\nabla}\cdot\left(\frac{1}{X^2}\vec{\nabla}\chi\right) = 2\pi J_\phi \tag{1}$$

where we use the standard (X, ϕ, Z) cylindrical coordinates, and where J_ϕ represents the perturbed currents from active feedback coils in the vacuum region and the eddy currents present in resistive passive conductors.

The corresponding Green's function is defined by

$$X_S\vec{\nabla}_T\cdot\frac{1}{X_T^2}\vec{\nabla}_T G(X_T, Z_T; X_S, Z_S) = 4\pi\delta(X_S - X_T)\,\delta(Z_S - Z_T) \tag{2}$$

The solution is well known and can be expressed in terms of complete elliptic integrals.

By integrating Eqns. (1) and (2) over the volume of the vacuum region we get a Green's equation that relates the perturbed vacuum flux to the currents in the vacuum region and to an integral over the boundary surfaces:

$$\chi(X_S, Z_S) = \sum_{m=1}^{M} J_m G(X_S, Z_S; X_m, Z_m) + \frac{1}{2\pi}\oint \frac{dl_T}{X_T}[\chi_T(\hat{n}\cdot\vec{\nabla}_T G_{TS}) - G_{TS}(\hat{n}\cdot\vec{\nabla}_T\chi_T)] \tag{3}$$

where S denotes the observation points and T denotes the source points, and where we define the feedback currents as follows:

$$J_m = k_m[\chi(X_{o1}, Z_{o1}) - \chi(X_{o2}, Z_{o2})] + l_m[\dot{\chi}(X_{o1}, Z_{o1}) - \dot{\chi}(X_{o2}, Z_{o2})]$$

The feedback current is thus proportional to a linear combination of the perturbed flux difference between two observation points symmetric about the midplane and the corresponding time derivative term. The surface integrals in Eq. (3) are over the surfaces that are the boundaries to the vacuum region, i.e., the plasma-vacuum surface and the surface of the resistive wall surrounding the plasma.

Separate Green's equations are obtained for the vacuum region between the plasma and the resistive wall, and for the region outside the resistive wall. Using the thin wall approximation, we get an expression that relates the jump in the normal derivative across the thin resistive wall boundary to the time derivative of the flux on the boundary:

$$[[(\hat{n}\cdot\vec{\nabla}\chi)]] = \frac{-i\omega\mu_0}{\eta}\,\delta\,\chi_w, \tag{4}$$

where [[ ]] denotes the jump across the thin resistive wall, δ is the thickness, and η is the resistivity of the wall. This relation can also be found by taking the Green's equation for the resistive wall region in the limit as the wall thickness goes to zero.

By finite differencing the quantities on the surface, we express the surface integrals in Eq. (3) as sums over the points on the surface. We then evaluate Eq. (3) repeatedly with every grid point on the surface serving once as the observation point (X_S, Z_S). This series of equations can be combined into a single matrix equation in which the integrals are expressed as matrices multiplying column vectors χ and $\nabla_n\chi$, which contain the values of the perturbed flux and its normal derivative at every grid point on the surface. We get a total of 3 matrix equations corresponding to the number of surfaces that bound the two regions (plasma, inner wall, and outer wall—the outer region extends to infinity). The equations for the case with active feedback coils and flux loops present in the region outside the resistive wall are as follows:

$$
\begin{aligned}
(\underline{\underline{1}} + M_{pp})\chi_p + M_{pw}\chi_w &= \hat{G}_{pp}\nabla_n\chi_p + \hat{G}_{pw}\nabla_n\chi_w \\
M_{wp}\chi_p + (\underline{\underline{1}} + M_{ww})\chi_w &= \hat{G}_{wp}\nabla_n\chi_p + \hat{G}_{ww}\nabla_n\chi_w \\
(\underline{\underline{1}} + M^+_{ww})\chi^+_w &= \hat{G}^+_{ww}\nabla_n\chi^+_w + P\chi_w + N\nabla_n\chi_w
\end{aligned}
\tag{5}
$$

where the matrices M and $\hat{G}$ are defined by

$$
M_{wp}\chi_p = -\frac{1}{2\pi}\oint_p \frac{dl_p}{X_p}(\hat{n}\cdot\vec{\nabla}G_{pw})\chi_p
$$

$$
\hat{G}_{pw}\nabla_n\chi_w = -\frac{1}{2\pi}\oint_w \frac{dl_w}{X_w}G_{wp}(\hat{n}\cdot\vec{\nabla}\chi_w)
$$

We denote the identity matrix with $\underline{\underline{1}}$. The + superscripts denote quantities on the outer surface of the thin resistive wall. The w subscript without the + superscript denotes the inner surface of the wall, and the p subscript denotes the plasma surface. The jump condition connecting $\nabla_n\chi^+_w$ with $\nabla_n\chi_w$ is given by Eq. (4); $\chi^+_w = \chi_w$ in the thin wall approximation. The matrices P and N contain the effects of the active feedback system. Since the active feedback currents are a linear function of the perturbed flux at the observation points, they can, after some algebra, be expressed in terms of matrix relations involving χ and $\nabla_n\chi$.

NOVA solves the eigenvalue problem given the plasma boundary condition of the perturbed pressure p_1 at the plasma-vacuum interface. The perturbed pressure p_1 at the P-V interface is found in terms of the normal derivative of the flux at the boundary:

$$
p_1 = \vec{B}\cdot\vec{b} = (\nabla\phi\times\nabla\psi)\cdot(\nabla\phi\times\frac{\nabla\chi}{2\pi}) = \frac{1}{2\pi X^2}(\nabla\psi\cdot\nabla\chi) \tag{6}
$$

The boundary condition at the plasma-vacuum interface that relates the magnetic perturbation $\vec{b}$ to the perturbation $\vec{\xi}$ of the plasma gives us a relation for the perturbed flux χ

$$
\vec{b} = \vec{\nabla}\times(\vec{\xi}\times\vec{B}) \;\Rightarrow\; \chi = -2\pi\xi_\psi\ , \tag{7}
$$

where

$$\xi_\psi = \vec{\xi} \cdot \vec{\nabla}\psi = \sum_l \xi_l \; exp(il\Theta) \tag{8}$$

By combining Eqs. (5) we solve for the normal derivative of the perturbed flux at the boundary, $\nabla_n \chi$, in terms of χ, which in turn is known as a function of the Fourier modes of the displacement ξ_l from in Eqs. (7) and (8).

We then perform a Fourier transform of the expression in Eq. (6) to get p_1 in terms of the Fourier modes

$$p_1 = \vec{b} \cdot \vec{B} = \sum_m p_m \, exp(im\Theta) \; = \sum_{m,m'} \tilde{M}_{m,m'} \, \xi_{m'} \, exp(im\Theta) \tag{9}$$

The matrix $\tilde{M}$ is the goal of the vacuum calculation. This matrix relates p_1 to the Fourier modes of ξ_ψ and includes the effects of the resistive conductors, the active feedback currents, and the geometry of the vacuum region.

Applications

We use the NOVA-W code to analyze the properties of active feedback systems of actual tokamak experiments with highly shaped cross sections such as PBX-M. In particular it is useful for examining different feedback laws for a given feedback system, and for examining the effect of feedback coil positions and (flux loop) observation points. NOVA-W is also used to calculate the linearized growth rate of the vertical instability in the presence of realistic passive resistive conductors surrounding the plasma in the vacuum region. We present results from the full 2-D NOVA-W code, as well as for a simplified 1-D large aspect ratio cylindrical model.

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Acknowledgments

This work is supported by U.S. DoE Contract DE-AC02-76CHO3073. One of the authors (DJW) is supported under the U.S. Air Force Office of Scientific Research Laboratory Graduate Fellowship Program.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David J. Ward   Semester: Spring 1989

University: Princeton University   Subcontract: S-789-000-023

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   please see attached sheet

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   please see attached sheet

"I certify that all information stated is correct and complete."

David J. Ward

Signature/Fellowship Recipient

David J. Ward   4th year graduate student, Princeton University

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 4967C

Courses

I did not take any University courses during the Spring Semester, 1989. I have been spending most of my time on my thesis research, and there were no particularly appropriate classes this semester.

DESCRIPTION OF RESEARCH TOWARDS DISSERTATION

As I explained in my last report, I have been in the process of modifying a non-variational tokamak plasma stability code to include the effects of resistive conductors and an active feedback system in the calculation of the vacuum boundary condition. I made these modifications and I am presently in the process of testing the code and applying it to various tokamak designs. I am also making further modifications. I reported on some of the early progress that I had made at The International Sherwood Theory Conference, April 3-5, 1989. I have included a copy of the abstract that appeared in the program booklet for this conference.

Last year I was working with my advisors on a paper that is of importance to my thesis. This paper, by N. Pomphrey, S. C. Jardin, and myself entitled **Feedback Stabilization of the Axisymmetric Instability of a Deformable Tokamak Plasma**, has now been published in the journal **Nuclear Fusion**. I have included a copy of this paper for your records. An additional paper that I was working on last year is due to be published in the next month or two. I will send along a copy of this paper as soon as it becomes available.

I have been very pleased with the progress I am making in my thesis research. It is very likely that in the next month or so I will begin working on a paper describing my work over the last year. This will also be expanded into several chapters of my dissertation. I expect to be able to finish my thesis research in little over 1 year, i.e. early fall of 1990.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. David J. Ward is making satisfactory academic progress toward a Ph.D. in the area of Plasma Physics in the discipline of Physics for the Spring 1989 semester."

Signature/Advising Professor

Stephen C. Jardin, Professor, Principal Research Physicist, Princeton Plasma Physics Laboratory

TYPED NAME/TITLE OF ADVISING PROFESSOR

4967C

Studies of Axisymmetric Modes in Tokamak Plasmas with Active and Passive Feedback *

D. J. Ward, S. C. Jardin, C. Z. Cheng

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08543

Deformable tokamak plasmas with highly shaped cross-sections are susceptible to axisymmetric ($n = 0$) instabilities. Complete stabilization of these modes may be possible by a combination of resistive walls and an active feedback system. Previous studies have shown, however, that both the stability of the system and the nature of the eigenmodes can depend strongly on the details of the active feedback system.[1] For example, it was found that for certain locations of the flux detection loops around the plasma cross-section the active feedback system was unable to completely stabilize the axisymmetric plasma motion regardless of the feedback gain.

To study these effects we are developing a plasma stability code that includes passive resistive conductors and an active feedback system within the plasma-vacuum model. These modifications will not fit into the framework of the self-adjoint δW formulation. Therefore we use the non-ideal, non-variational stability code NOVA.[2] We have modified the vacuum calculation of the NOVA code to include resistive passive conductors. We will also add the ability to account for currents from active feedback coils based on poloidal flux measurements. Details of these modifications and the results from some test cases will be given.

[1] N. Pomphrey, S. C. Jardin, and D. J. Ward, Princeton Plasma Physics Laboratory Report # PPPL-2468-R (October 1988). Accepted for publication in Nuclear Fusion.

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*Work supported by U.S. DoE Contract # DE-ACO2-76-CHO3073.

FEEDBACK STABILIZATION OF THE AXISYMMETRIC INSTABILITY OF A DEFORMABLE TOKAMAK PLASMA

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ABSTRACT. The paper presents an analysis of the magnetohydrodynamic stability of the axisymmetric system consisting of a free boundary tokamak plasma with non-circular cross-section, finite resistivity passive conductors, and an active feedback system with magnetic flux pickup loops, a proportional amplifier with gain G and current carrying poloidal field coils. A numerical simulation of the system when G is set to zero identifies flux loop locations which correctly sense the plasma motion. However, when certain of these locations are incorporated into an active feedback scheme, the plasma fails to be stabilized, no matter what value of the gain is chosen. Analysis on the basis of an extended energy principle indicates that this failure is due to the deformability of the plasma cross-section.

1. INTRODUCTION

It is well known that tokamak plasmas with elongated cross-sections are subject to a pernicious axisymmetric magnetohydrodynamic (MHD) instability and must be stabilized by the placement of nearby passive conductors, and by an active feedback system which responds on the resistive time-scale of these conductors [1–8]. Most previous analyses of the stability of such a feedback system have considered the case of a deformable plasma stabilized by perfectly conducting passive conductors only [1, 3], or the case of a rigid filamentary plasma with resistive conductors and an active feedback system [2]. Here we discuss important new effects present in the more realistic configuration consisting of a finite-size deformable plasma, resistive conductors and an active feedback system. We also discuss the importance of the low frequency limit of this system in which the resistive conductors do not enter the analysis.

The components of an active feedback system include: (1) a means of observing the plasma motion, for example magnetic flux pickup loops, (2) a set of current carrying feedback coils positioned so that they produce a magnetic field which opposes the unstable plasma motion, and (3) an amplifier system which transforms the observed flux measurements into a voltage signal at the coils. It is clear that the placement of the feedback coils is important. However, we will show in this paper that the correct placement of the flux loops is also critical: despite a placement which correctly senses the vertical motion of the plasma, the instability may fail to be stabilized by any value of the gain. We demonstrate this effect by analysing the results of a numerical simulation relevant to the Princeton Beta Experiment (PBX) [9, 10]. We use Bode diagram and Nyquist techniques for the analysis. Similar results are found in an analytic calculation which applies the energy principle of ideal MHD to a straight plasma with rectangular cross-section and constant current density. The successful design of feedback systems for future experiments must consider the correct placement of flux pickup loops as a critical issue.

2. NUMERICAL SIMULATION RESULTS

Figure 1 shows a schematic of a shaped plasma for which position control is a necessary element of the design. The plasma carries 0.75 MA current and has a cross-section that is elongated and indented on the inboard side. Conducting plates surrounding the plasma lead to passive stabilization on the ideal MHD time scale. The L/R time for the passive conductors is 100 ms. The poloidal field coil system used for equilibrium, shaping and feedback control is shown, as are two pairs of observation points. The flux difference between the top and bottom members of these pairs is a measure of the displacement of the

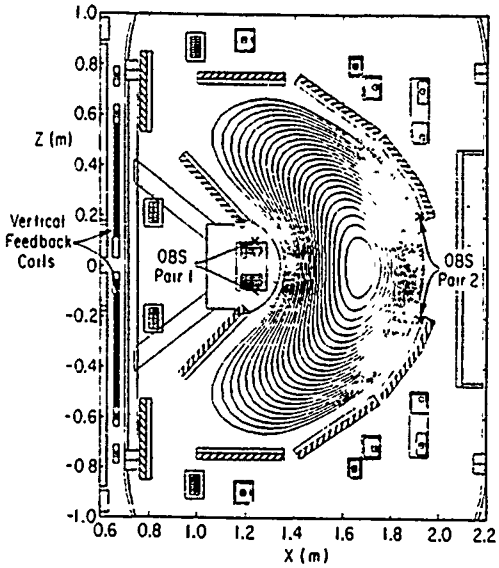

FIG. 1. Schematic of the Modified Princeton Beta Experiment (PBX-M). The inboard and outboard observation pairs used for feedback control in the numerical simulations are denoted by crosses.

plasma from its equilibrium position on a midplane. Apart from the location of these pickup loops, the system shown in Fig. 1 is an accurate representation of the modified Princeton Beta Experiment (PBX-M) [11].

We have used the Princeton Tokamak Simulation Code (TSC) [12] to analyse issues of vertical position control for the configuration described above. The TSC accurately models the transport time-scale evolution of axisymmetric plasmas, including the plasma interaction with passive and active feedback systems. For the simulations described below, we employ a simple feedback control law requesting an incremental current from the vertical feedback coils in proportion to the measured flux imbalance between one or other of the observation pairs, i.e.

$$I_W(t) = \beta \times [\psi_i^{top}(t) - \psi_i^{bottom}(t)] \qquad (1)$$

where i = 1 refers to the inboard observation pair and i = 2 refers to the outboard observation pair.

In the passive sense, the inboard observation pair and the outboard observation pair are equally good at detecting the vertical motion of the plasma. This is illustrated in Fig. 2, Case A, which shows the results of a simulation where the active feedback system is turned off by setting the gain β equal to zero. The flux differences $\Delta\psi_i(t) = \psi_i^{top}(t) - \psi_i^{bottom}(t)$ are plotted as a function of time for each observation pair. We see that the same growth rate for the instability is calculated by the TSC using either observation pair, and that the amplitude of the flux detected by each pair of loops is essentially the same, corresponding to a nearly rigid displacement. We now show that despite the fact that both observation pairs detect the unstabilized motion equally well, only the outboard pair can be successfully incorporated into the active feedback scheme defined by Eq. (1).

To investigate the stability of the feedback system, we adopt some techniques of control engineering [13]. Figure 3 is a block diagram for the system; it shows the relationship between components, and the flow of signals from input to output. A reference current signal is input in the vertical feedback coils, the plasma/conductor/vacuum MHD equations are advanced by the TSC, and the measured flux difference between a

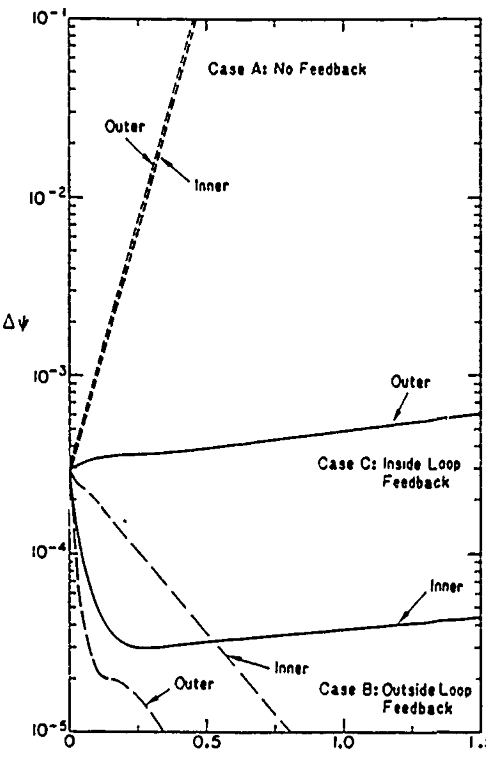

FIG. 2. Flux differences, $\Delta\psi_i(t) = \psi_i^{top}(t) - \psi_i^{bottom}(t)$, for the inner and outer observation pairs, plotted as a function of time.
Case A. Simulation results when the feedback gain β is zero. The same growth rate is obtained using either observation pair.
Case B: Active feedback with the feedback coils connected to the outside flux loops. The plasma is stable.
Case C: Active feedback with the feedback coils connected to the inside flux loops. The plasma is unstable.
The same feedback gain values were used in Cases B and C.

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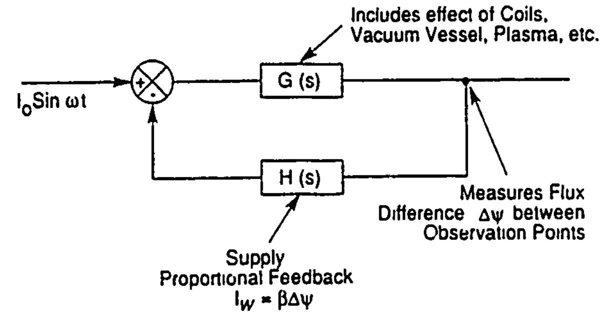

FIG. 3. Block diagram for the frequency response analysis of the control system.

pair of observation points is output. The feedback loop is closed by amplifying the output and returning it to the feedback coils as a current correction to the reference signal. For stability, all poles of the closed-loop transfer function, $T(s) = G(s)/[1 + \beta G(s)]$, must have negative real parts. The location of these poles is determined by the encirclement theorem, which leads to the Nyquist criterion for stability:

$$\frac{1}{2\pi}[\Delta \arg(1 + \beta G(s))]_{-i\infty}^{+i\infty} = N_p \qquad (2)$$

The phase change of the transfer function on the left-hand side can be interpreted as the number of counter-clockwise encirclements of the point (-1,0) by the $\beta G(s)$ locus as s is increased from $-i\infty$ to $+i\infty$, and N_p is the number of poles of $\beta G(s)$ having positive real parts. For a vertically unstable plasma partially stabilized by resistive walls, it is possible to show that $N_p = 1$.

The open-loop transfer function G(s) is not expressed in closed form for our problem and must be evaluated numerically. To do this, we input a test signal in the feedback coils in the form of a sinusoid with frequency ω. The steady state response characteristics of a stable system are such that $|\beta G(i\omega)|$ is equal to the amplitude ratio of the output and input sinusoids, and $\arg[\beta G(i\omega)]$ is the phase shift of the output sinusoid with respect to the input sinusoid. The data are collected on opposite sides of the summing point (see Fig. 3).

Figure 4 presents results obtained from running the TSC, using first the inboard observation pair and then the outboard observation pair for monitoring the flux. The sign and magnitude of the gain are the same for both cases. The results are shown as a Bode diagram, which consists of two graphs: one is a plot of $\log|\beta G(i\omega)|$ versus ω, the other is a plot of $\arg[\beta G(i\omega)]$ versus ω. Once the Bode diagram is constructed, the Nyquist plots follow readily. We see that use of the outboard observation pair gives rise to a closed curve which meets the conditions required by the Nyquist stability criterion. On the other hand, the Nyquist curve obtained using the inboard observation pair not only fails to enclose the point (−1,0) but is also described in the wrong sense. Since changing beta simply scales the distance of each point on a curve to the origin but leaves the sense of traversal unchanged, the feedback system which uses the outboard observation pair will be stable for a finite range of beta, corresponding to the enclosure of (−1,0), whereas the feedback system which uses the inboard observation pair will be unstable for all values of beta.

The essential difference in behaviour of the two feedback systems is the response to low frequencies. At very high frequency, the signal from the feedback coils is unable to affect the plasma motion because it cannot penetrate the intervening passive conductors. The feedback system is completely passive in this

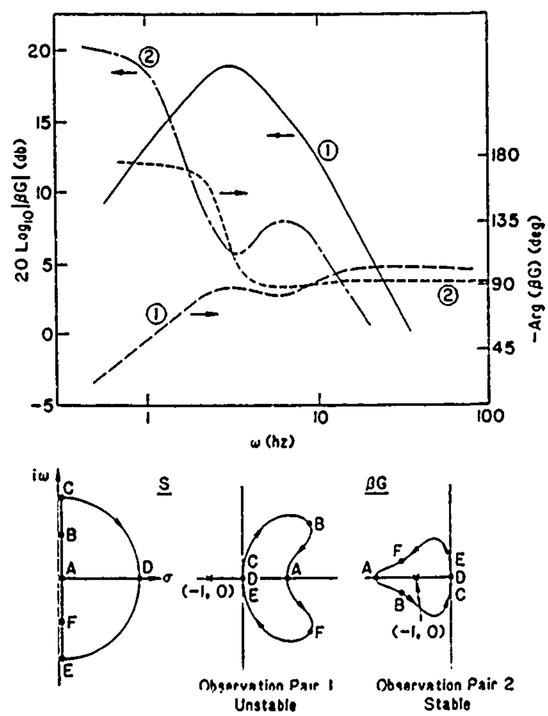

FIG. 4. Top: Frequency dependence of the amplitude and phase of the transfer function G when observation pairs 1 and 2 are used to monitor the flux.
Bottom: Nyquist curves resulting from the mapping to the complex G plane.

limit. If the frequency is lowered, to become comparable to the inverse L/R time of the conductors, the signal has time to influence the plasma motion. The influence is seen in the Bode plots as a dramatic change in slope in the curves of amplitude and phase. When the frequency is lowered towards the zero frequency limit. the contrast between the two observation points is most clear. In this limit, the passive stabilizers are completely transparent to the feedback signal and, therefore, cannot affect the feedback response of the plasma. It is in this low frequency limit that the placement of the flux detection loops can determine the overall stability of the system.

To further illustrate the effect seen in the Bode plots, we show two initial-value, time dependent simulations with the TSC using the same initial conditions for the plasma as in the passive calculation (Case A of Fig. 2), but with the feedback system activated and connected to the outside flux loops (Case B) or the inside flux loops (Case C). For each simulation the feedback gain had the same value as in the frequency domain analysis of Fig. 4. The results are shown in Fig. 2.

For Case B, where the feedback system is connected to the outer observation pair, the plasma motion is seen to be stabilized. The flux differences measured by the inner and the outer observation pairs both decrease with time, with the flux difference between the outer loops almost an order of magnitude less than the flux difference between the inner loops. This indicates some plasma distortion. For Case C, where the feedback system is connected to the inboard observation pair, the plasma remains unstable, albeit with a much reduced growth rate. The flux difference between the inner observation loops is now an order of magnitude less than the flux difference between the outer loops, also indicating a plasma distortion, but one whose detailed form is different compared with Case B.

In summary, the unstable eigenfunction depends on the position of the flux loops used to detect the motion, even though the feedback coils, in which the feedback currents appear, are exactly the same in the two cases. We now investigate stability in the low frequency limit with an analytic model.

3. ANALYTIC MODEL

A plasma column of a constant current density and square cross-section is unstable to a non-rigid axisymmetric (n = 0) instability [14]. Here we modify the analysis of Ref. [14] to include an active feedback system and we show that there are forbidden regions for the placement of the pickup loops if stability is to be ensured. For the straight plasma, the equilibrium poloidal flux ψ satisfies $\nabla^2 \psi = j_z$. We choose j_z = constant, and

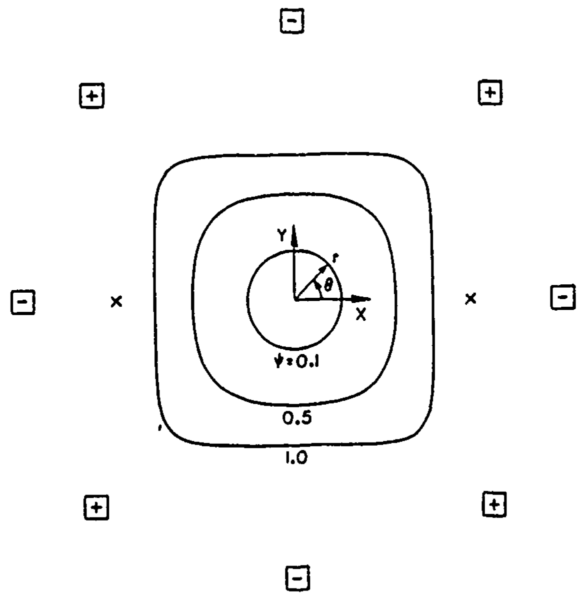

FIG. 5. Contours of constant flux for the analytic model. The equilibrium magnetic field is produced by coils which push on the sides and pull at the corners. A pair of crosses on the midplane denote a typical observation pair for monitoring the position instability.

$$\psi = r^2 + \alpha r^4 \cos 4\theta \tag{3}$$

Here, α is a squareness parameter, which is assumed to be small. If $\alpha = 0$, then the plasma-vacuum interface ($\psi = 1$) is a circle. Even modest values of α, such as $\alpha = 0.2$, make the $\psi = 1$ surface nearly square. Figure 5 shows a schematic of the plasma, the poloidal field coils and typical pairs of observation coils.

The δW of the energy principle can be written as separate contributions from the plasma and from the vacuum:

$$2\delta W = \int_p [(\nabla\phi_p)^2 + j_z \xi \cdot \nabla\phi_p] dA + \int_v [(\nabla\phi_v)^2 + \phi_v \nabla^2 \phi_v] dA \tag{4}$$

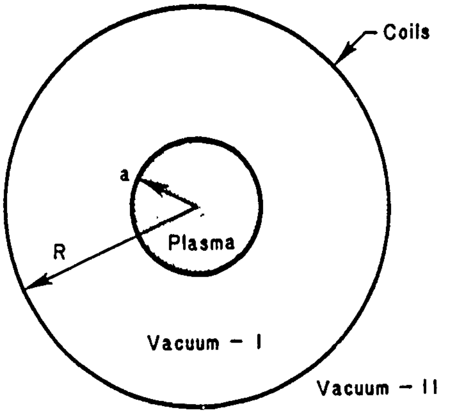

FIG. 6. Plasma and vacuum regions for the analytic calculation.

where ϕ is the perturbed flux function, ξ is the fluid displacement, and the subscripts p and v refer to plasma and vacuum, respectively. To evaluate this expression for the given model, it is convenient to express δW in terms of the flux co-ordinates (ψ,θ,z). Thus, we write

$$2\delta W = \int\int d\psi d\theta \mathcal{J}(\nabla\phi_p)^2 - j_z \oint d\theta \mathcal{J}\phi_p^2 - \oint d\theta \mathcal{J}\phi_v(\nabla\psi\cdot\nabla\phi_v) \quad (5)$$

where

$$(\nabla\phi_p)^2 = (\nabla\psi)^2(\frac{\partial\phi_p}{\partial\psi})^2 + 2\nabla\psi\cdot\nabla\theta(\frac{\partial\phi_p}{\partial\psi})(\frac{\partial\phi_p}{\partial\theta}) + (\nabla\theta)^2(\frac{\partial\phi_p}{\partial\theta})^2 \quad (6)$$

and

$$\mathcal{J} = (\nabla\psi\cdot\nabla\theta\times\nabla z)^{-1} = \frac{1}{2}\frac{dr^2}{d\psi} \quad (7)$$

is the Jacobian. The integral denoted by $\oint$ is evaluated around the $\psi = 1$ contour, and $j_z = 4$ in the units of Eq. (3). Since α is small, Eq. (3) can be inverted to obtain r(ψ,θ), from which the metric elements and the Jacobian can be evaluated.

The procedure for evaluating δW follows the description given in Ref. [14], but with the perturbed vacuum flux modified by the presence of current carrying feedback coils. Figure 6 shows a schematic of the plasma and vacuum regions for the analytic calculation. The perturbed vacuum flux is given the following representation:

In region I,

$$\phi_v^I(r,\theta) = \sum_{m=1}^{\infty} B_m^I r^{-m}\cos m\theta + \sum_{m=1}^{\infty} L_m r^m \cos m\theta \quad (8)$$

In region II,

$$\phi_v^{II}(r,\theta) = \sum_{m=1}^{\infty} B_m^{II} r^{-m}\cos m\theta \quad (9)$$

The two vacuum regions are separated by a circular contour, of radius R, upon which the feedback coils lie. The second term in Eq. (8) is the multipolar decomposition of the flux from these coils. Each of the terms in the sum is interpreted as the flux from an 'equivalent feedback system' made up of m identical coils, equally spaced on the circular contour. The m = 0 terms in Eqs (8) and (9) are absent since they have zero gradient. In the plasma, the perturbed flux is given the form

$$\phi_p(\psi,\theta) = \sum_{m=0}^{\infty} D_m(\psi)\cos m\theta \quad (10)$$

Upon substituting Eqs (8)–(10) into Eq. (5) for δW, applying the appropriate matching conditions at the boundaries between regions I and II in the vacuum and at the plasma–vacuum interface (see Appendix), and repeated use of Euler's equation to minimize the plasma contributions to δW with respect to the Fourier coefficients, the following expressions for the energy and eigenfunction are obtained:

$$\frac{2\delta W}{\pi} = \alpha[-2D_1L_1^\alpha] + \alpha^2[-\frac{21}{4}D_1^2 + 4D_1D_3^\alpha + 4D_1D_5^\alpha + 2\sum_{m=1}^{\infty}(m-1)(D_m^\alpha)^2 - 2D_1L_1^{\alpha\alpha} + \frac{3}{2}D_1L_3^\alpha + \frac{5}{2}D_1L_5^\alpha - 2\sum_{m=1}^{\infty} mD_m^\alpha L_m^\alpha] \quad (11)$$

$$\xi_r^0 - 2\alpha r\xi_r^\alpha = -\frac{1}{2}D_1\cos\theta + \alpha[r\cos\theta D_1^\alpha + r^3\cos 3\theta(D_3^\alpha - \frac{7}{4}D_1) + r^5\cos 5\theta(D_5^\alpha + \frac{1}{4}D_1) + \sum_{m\neq 1,3,5}^{\infty} r^m \cos m\theta D_m^\alpha] \quad (12)$$

$$\xi_\theta^0 + 2\alpha r\xi_\theta^\alpha = +\frac{1}{2}D_1 \sin\theta$$

$$+ \alpha[r \sin\theta D_1^\alpha + r^3 \sin 3\theta(D_3^\alpha - \frac{7}{4}D_1)$$

$$+r^5 \sin 5\theta(D_5^\alpha + \frac{1}{4}D_1) + \sum_{m\neq 1,3,5}^{\infty} r^m \sin m\theta D_m^\alpha] \tag{13}$$

In these equations the Fourier coefficients D_m are evaluated at the plasma edge, $\psi = 1$. The alpha orderings are shown explicitly so that D_m^α represents the first-order piece of D_m, etc.

So far, we have not specified any details of the feedback system. By analogy with the numerical experiment reported in the previous section, we let each feedback system respond to the plasma motion by generating coil currents in proportion to some linear combination of perturbed flux. Schematically,

$$L_m = G_{mn}\Delta\phi_v(D_n) \tag{14}$$

If the gain matrix G has the correct symmetry properties (see Appendix), this form of feedback law can be shown to leave the stability operator self-adjoint, so that the energy principle will still apply. The gain elements G_{mn} should be at least of the order of α, so that the feedback system has no effect when α is zero. (A circular plasma is motionally stable.) Hence, $L_m^\alpha = G_{mn}^\alpha(\Delta\phi_v^0)$. Equation (8) for ϕ_v shows that $\Delta\phi_v^0$ is proportional to D_1, with a constant of proportionality that depends on the location of the observation points. If we absorb the constant of proportionality into the G-symbol for the gain, the first-order contribution to the energy becomes

$$\frac{2\delta W^\alpha}{\pi} = -2G_{11}^\alpha(D_1)^2 \tag{15}$$

Thus, to first order in α, the system stability depends only on the sign of G_{11}^α.

Suppose now that $L_1^\alpha = 0$. Then, δW^α vanishes, and stability is determined by the second-order terms in δW. To simplify the analysis of $\delta W^{\alpha\alpha}$, we choose a simplified feedback model motivated by the form of the eigenfunction without feedback: Since the zeroth-order displacement eigenfunction is a rigid shift, it is appropriate to set the rigid shift component of the first-order displacement equal to zero, i.e. $D_1^\alpha = 0$. When δW is minimized with respect to the D_m's, we obtain $D_3^\alpha = -\frac{1}{2}D_1$, $D_5^\alpha = -\frac{1}{4}D_1$ and $D_m^\alpha = 0$ for $m \neq 3, 5$. The minimizing eigenfunction (first order) is, therefore,

$$\xi_r^\alpha = \frac{9}{8}r^2 D_1 \cos 3\theta \ , \ \xi_\theta^\alpha = -\frac{9}{8}r^2 D_1 \sin 3\theta \tag{16}$$

which is an $m = 3$ wrinkle superimposed on the rigid shift [14]. The simplest non-trivial feedback model we can choose to make δW self-adjoint (see Appendix) is, therefore,

$$L_1^{\alpha\alpha} = G_{11}^{\alpha\alpha}D_1 + G_{13}^\alpha D_3^\alpha$$

$$L_3^\alpha = \frac{1}{3}G_{13}^\alpha D_1 \tag{17}$$

$$L_m^\alpha = 0 \qquad m > 3$$

This corresponds to coils with an ability to respond (on account of the flux measurements) to both the rigid shift and the $m = 3$ perturbations.

We substitute these feedback terms into the expression for δW, Eq. (11). For a trial displacement, we use the eigenfunction found for the system without feedback, given in Eq. (16). The calculated δW with the feedback terms included is

$$\frac{2\delta W}{\pi} = \alpha^2 D_1^2[-\frac{27}{4} - 2G_{11}^{\alpha\alpha} + \frac{5}{2}G_{13}^\alpha] \tag{18}$$

Without feedback ($G_{11}^{\alpha\alpha} = G_{13}^\alpha = 0$), the plasma is seen to be unstable. With feedback, δW can be made positive for a range of values of the gain coefficients. Specifically, for any choice of G_{13}^α, a $G_{11}^{\alpha\alpha}$ can be found which is stabilizing. The converse is also true. This can be seen in Fig. 7, which gives the stability boundary for this trial displacement in $(G_{11}^{\alpha\alpha}, G_{13}^\alpha)$ parameter space.

Now let us consider the effect of the feedback system on the eigenfunction. We take our expression for δW, Eq. (11), with the feedback terms included and minimize with respect to the D_m^α. This yields $D_3^\alpha = [-\frac{1}{2} + \frac{1}{2}G_{13}^\alpha]D_1$, $D_5^\alpha = -\frac{1}{4}D_1$ and $D_m^\alpha = 0$ for $m \neq 3, 5$.

The minimized δW is

$$\frac{2\delta W}{\pi} = \alpha^2 D_1^2[-\frac{27}{4} - 2G_{11}^{\alpha\alpha} + \frac{5}{2}G_{13}^\alpha - (G_{13}^\alpha)^2] \tag{19}$$

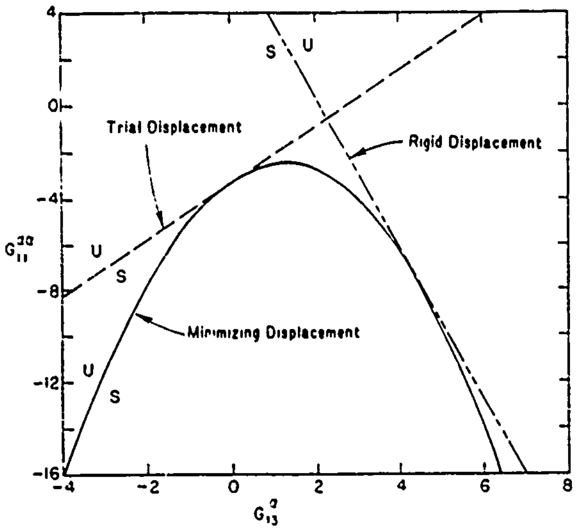

FIG. 7. Stable and unstable regions for a range of values of the gains $G_{11}^{\alpha\alpha}$ and G_{13}^{α}. The long-dashed line represents the stability boundary for the trial displacement given in Eq. (16). The short-dashed line represents the stability boundary for the rigid displacement. The solid curve denotes the stability boundary for the minimized eigenfunction that is deformed by the feedback system. The regions in the ($G_{11}^{\alpha\alpha}, G_{13}^{\alpha}$) parameter space where the plasma is stable or unstable are marked on either side of the stability boundary by S and U, respectively.

with the corresponding (first-order) eigenfunction

$$\xi_r^\alpha = D_1 r^2\left(\frac{9}{8} - \frac{G_{13}^\alpha}{4}\right)\cos 3\theta$$

$$\xi_\theta^\alpha = -D_1 r^2\left(\frac{9}{8} - \frac{G_{13}^\alpha}{4}\right)\sin 3\theta \qquad (20)$$

The last two terms in δW are seen to be stabilizing for $0 < G_{13}^\alpha < 5/2$, and optimally stabilizing for $G_{13}^\alpha = 5/4$. For this optimal value, the mode is stabilized if $G_{11}^{\alpha\alpha} < 83/32$. This is summarized in Fig. 7, which shows the stable and unstable boundaries for this minimized δW in the ($G_{11}^{\alpha\alpha}, G_{13}^\alpha$) parameter space. It is seen that for any choice of G_{13}^α, a $G_{11}^{\alpha\alpha}$ can be found which stabilizes the mode. However, the converse is not true, and the choice of $G_{11}^{\alpha\alpha}$ is critical. Since the actual values of the G-gains depend on the location of the observation points, we see that this result translates into a criticality for the placement of the flux pickup loops.

It is also interesting to consider the conclusions that result from restricting the instability to take the form of a rigid displacement. These indicate that the above behaviour is due to the ability of the feedback systems to distort the eigenfunction. For a rigid displacement, we must choose (see Eq. (12)) $D_3^\alpha = \frac{7}{4} D_1$, $D_5^\alpha = -\frac{1}{4} D_1$ and $D_m^\alpha = 0$ for $m \neq 3, 5$. Then the expression for δW becomes

$$\frac{2\delta W}{\pi} = \alpha^2 D_1^2\left[\frac{27}{2} - 2G_{11}^{\alpha\alpha} - \frac{13}{2}G_{13}^\alpha\right] \qquad (21)$$

The stable and unstable regions for this rigid instability are also shown in Fig. 7. Because of the linearity of δW on the G's, it follows that a $G_{11}^{\alpha\alpha}$ can be found to stabilize the mode for any value of G_{13}^α. The converse is also true. Therefore, for a rigid instability, the detailed placement of flux pickup loops for monitoring the motion is not critical. Note that the stable/unstable boundary for the rigid instability encloses the stable region for the deformable instability, except for a common point at $G_{13}^\alpha = 9/2$. Equation (20) shows that for this value of the gain, G_{13}^α, the eigenfunction no longer supports an m = 3 deformation, so that the eigenfunctions for the rigid and deformable instability coincide.

The stable/unstable boundary for the trial displacement, given by Eq. (16), also encloses the stable region for the deformable instability. It is clear that the minimizing eigenfunction, Eq. (20), is affected by the feedback and this results in a plasma that can only be stabilized by feedback where the gain $G_{11}^{\alpha\alpha}$ lies within a restricted region. Thus we see that the feedback system with certain placements of the observation points can allow the unstable eigenfunction to deform so that the plasma will remain unstable.

4. CONCLUSIONS

We have demonstrated the usefulness of a new technique for analysing the stability and control properties of an axisymmetric tokamak using the time dependent simulation code TSC to perform frequency domain analysis. Using this technique, we find that in the PBX-M tokamak, certain placements of the magnetic pickup coils, on the inboard side, lead to an unstable system, regardless of the gain, whereas other placements, on the outboard side, will give a stable system for sufficiently large values of the gain. A simplified analytic model suggests that this behaviour results from the non-rigid deformable nature of the plasma cross-section and from the plasma's ability to modify its unstable eigenfunction according to the particular feedback system. No such effect is present when the plasma is modelled as a current filament, a finite size rigid conductor or a 'trial function' displacement determined in the absence of feedback.

We can interpret this phenomenon qualitatively in terms of a simple physical picture. As part of the plasma instability, a perturbed magnetic field is produced in the vacuum region and this is sensed by the magnetic pickup coils. If the plasma is unstable enough, it can modify its eigenfunction to deform its cross-section so that a null in the perturbed vacuum magnetic field will appear at the position of the observation loops. Since these loops will then be unable to detect the plasma instability, the feedback system will be rendered inoperative.

We also emphasize the importance of the two limiting cases for stability analysis of this system. For frequencies that are large compared to the plate resistive times, we can treat the plates as perfect conductors, neglect the active feedback system and perform standard ideal MHD analysis of the system. In the opposite limit – that of very low frequencies – the conducting plates are transparent and do not enter the analysis. In this limit, the system must be considered as consisting only of a deformable plasma and active feedback.

Appendix

SELF-ADJOINTNESS OF δW IN THE PRESENCE OF A FEEDBACK SYSTEM

Since the first two terms in the expression for δW, Eq. (5), are manifestly self-adjoint, our discussion can be limited to the vacuum contribution

$$\delta W_v = -\oint d\theta \mathcal{J} \phi_v (\nabla\psi \cdot \nabla\phi_v)$$

$$= \int_v [(\nabla\phi_v)^2 + \phi_v \nabla^2 \phi_v] dA \qquad \text{(A.1)}$$

The first term on the right-hand side of Eq. (A.1) is again clearly self-adjoint. In the second term, let

$$\phi_v = \sum_{m=0}^{\infty} \phi_v^m(r) \cos m\theta \qquad \text{(A.2)}$$

Also, let the feedback coils be located in the vacuum at a radius r = R. Then

$$\nabla^2 \phi_v = \sum_{m=0}^{\infty} \frac{1}{\pi R} \delta(r - R) J_0^m \cos m\theta \qquad \text{(A.3)}$$

Using Eqs (A.3) and (A.2), the second term of Eq. (A.1) becomes

$$\delta W_v^{(2)} = \sum_{m=1}^{\infty} \phi_v^m(R) J_0^m \qquad \text{(A.4)}$$

Consider now a feedback law which relates the coil currents to the perturbed flux at the coils according to

$$J_0^m = \sum_{n=1}^{\infty} g_{mn} \phi_v^n(R) \qquad \text{(A.5)}$$

We see that if the gain matrix g_{mn} is symmetric, i.e.

$$g_{mn} = g_{nm} \qquad \text{(A.6)}$$

then $\delta W_v^{(2)}$, and hence δW_v, is self-adjoint.

The symmetry restriction on g_{mn} constrains the relationship between the feedback currents L_m and the Fourier coefficients D_m of the perturbed flux on the plasma-vacuum boundary. This relationship is obtained in two stages. In the first stage, the matching conditions for the vacuum flux are applied at the boundary between regions I and II in the vacuum (see Fig. 6). In the second stage, the matching conditions are applied at the plasma-vacuum interface.

Stage 1

Continuity of ϕ_v at r = R gives

$$B_m^I + L_m R^{2m} = B_m^{II} \qquad \text{(A.7)}$$

while the jump condition for $\partial\phi_v/\partial r$ at r = R (see Eq. (A.3)) is

$$B_m^I - L_m R^{2m} = B_m^{II} + \frac{J_0^m R^m}{m\pi} \qquad \text{(A.8)}$$

Thus,

$$L_m = -\frac{R^{-m}}{2\pi m} J_0^m \qquad \text{(A.9)}$$

Inserting Eq. (A.9) into Eq. (8) of Section 3, using definition (A.5), and then solving for $\phi_v^m(r)$ at r = R gives

$$\phi_v^m(R) = [\delta_{mn} + \frac{1}{2\pi m} g_{mn}]^{-1} B_n^I R^{-n} \qquad (A.10)$$

If, now, we define the matrix

$$C_{mn} = -\frac{R^{-m}}{2\pi m} g_{mn} R^{-n} [\delta_{mn} + \frac{1}{2\pi m} g_{mn}]^{-1} \qquad (A.11)$$

then Eq. (A.9) relates the region I vacuum coefficients B_m^I to the feedback currents L_m, according to

$$L_m = C_{mn} B_n^I \qquad (A.12)$$

Stage 2

Continuity of flux across the plasma-vacuum interface implies that

$$\sum_{m=0}^{\infty} D_m \cos m\theta = \sum_{m=1}^{\infty} B_m^I r^{-m} \cos m\theta + \sum_{m=1}^{\infty} L_m r^m \cos m\theta \qquad (A.13)$$

where

$$r^m = 1 - \frac{m}{2} \alpha \cos 4\theta \quad \text{at } \psi = 1 \qquad (A.14)$$

Equating Fourier coefficients on each side of Eq. (A.13), solving for B_m^I in terms of D_m and L_m, and substituting into Eq. (A.12) gives the matrix equation

$$L_m = G_{mn} D_m \qquad (A.15)$$

For the simplified 2 X 2 feedback system discussed in Section 3, the restriction that g_{mn} is symmetric to make δW self-adjoint, leads to Eq. (17).

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge stimulating conversations and continuing encouragement from Drs K. Bol, M. Okabayashi, M. Reusch, and others in the PBX group.

This work was supported by the United States Department of Energy, under Contract No. DE-AC02-76-CHO-3073. One of the authors (DJW) was supported by the United States Air Force under its Laboratory Graduate Fellowship Program.

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(Manuscript received 10 August 1988
Final manuscript received 16 December 1988)

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David J. Ward

Semester: Fall 1988

University: Princeton University

Subcontract: S-789-000-023

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Astrophysical Sciences 560 -- Computational Methods in Plasma Physics

Analysis of methods for the numerical solution of the partial differential equation of plasma physics, including those of elliptic, parabolic, hyperbolic, and eigen-value type. Topics include finite difference, finite element, spectral, particle-in-cell, Monte Carlo, moving grid, and multiple-time-scale techniques, applied to the problems of plasma equilibrium, transport, and stability.

(Description taken from Princeton University Graduate School Bulletin, 1988-89)

Grade received: Pass

(Courses in Astrophysical Sciences are graded on a Pass/Fail basis only).

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I am presently in the process of modifying a non-variational tokamak plasma stability code to include the effects of resistive conductors and an active feedback system in the calculation of the vacuum region boundary condition. This code is being developed in order to study the effect of active and passive feedback systems on the axisymmetric stability of a deformable tokamak plasma. These modifications are partially complete, and I am now writing a code to test this in a simplified limit, before merging this calculation with the full 3 dimensional plasma stability code NOVA.[1]

"I certify that all information stated is correct and complete."

David J. Ward

Signature/Fellowship Recipient

David J. Ward 4th year graduate student, Princeton University

TYPED NAME/FELLOWSHIP RECIPIENT

[1] C.Z. Cheng & M.S. Chance, Journal of Computational Physics, 71 (1987) 124.

LLD/sdp 4967C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. David J. Ward is making satisfactory academic progress toward a Ph.D. in the area of Plasma Physics in the discipline of Physics for the Fall 1988 semester."

Stephen C. Jardin

Signature/Advising Professor

Stephen C. Jardin, Associate Professor, Principal Research Physicist, Princeton Plasma Physics Laboratory

TYPED NAME/TITLE OF ADVISING PROFESSOR

4967C

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Jeffrey A. Young, studying Expert Systems (Vision) at ~~Stanford~~ Purdue University.

Give a brief statement of laboratory and/or Mr. Michael Wicks's (fellow's mentor) involvement with Mr. Jeffrey A. Young.

Chief Scientist Date

5 May 89

Mentor Date

S-789-000-024

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Jeffrey A. Young

Semester: Fall 1988

University: Purdue University

Subcontract: S-789-000-024

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

EE 608 Computational Models and Methods: Analysis of algorithm complexity. Data Structures for lists, graphs, trees and subsets to "large" and "small" universal sets. The design and complexity analysis of algorithms for searching, sorting, set operations, graph algorithms, matrix multiplication, polynomial evaluation and FFT calculations.
GRADE: A.

EE 662 Pattern Recognition and Decision Making Processes: Topics include various classifier design methodologies, evaluation of classifiability, learning machines, feature extraction and modeling.
GRADE: A.

EE 698 Research credit, grade: satisfactory (of u,s)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Produced a paper loosely based upon the same subject as my Masters Thesis: The Bhattacharyya Distance and the Gauss Assumption for Radar data. The paper was submitted to the IEEE AES journal to be considered for publicatior Completed the Ph.D. examination (taken in January before the Spring semester). This examination must be successfully completed in order to continue in the Ph.D. Program at Purdue.

"I certify that all information stated is correct and complete."

Jeffrey Young
Signature/Fellowship Recipient

Jeffrey Young
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5174C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Jeffrey A. Young is making satisfactory academic progress toward a Ph.D. in the area of Digital Signal Processing in the discipline of Electrical Engineering for the Fall 1988 semester."

Kenosuke Fukunaga
Signature/Advising Professor

TYPED NAME/TITLE OF ADVISING PROFESSOR

K. Fukunaga
Professor of Electrical Engineering

5174C

Statement of Progress Fall 1988

The work done this semester consisted of both experimental and theoretical investigations of second harmonic generation (SHG) and refractive grating formation in optical fibers. The experimental work involved gathering and setting up the necessary equipment for investigating nonlinear effects in optical fibers. Two optical tables were moved into the lab and joined together to form one large working surface, floated on air suspension legs to minimize vibration. A Nd:YAG laser and a large frame argon ion laser were installed and tested. A computer system was purchased and configured for data acquisition and numerical calculations. An optical multichannel analyzer was purchased for use in studying the spectra produced by the various nonlinear effects in the fibers. Preliminary studies of SHG in optical fibers were conducted to test the entire setup and as the first step in our set of planned experiments. We looked at the mode structure, spectrum and polarization of SH produced in a short piece of fiber.

The other major task last semester was a theoretical analysis of SHG in optical fibers. The aim is to model the effect using photorefractive theory. The basic idea is that the high intensity light in the fiber core excites charge carriers into the conduction band, allowing them to move fairly easily for short distances in the glass fiber. If there is a beating between any two fiber modes (Different modes travel down the fiber at different speeds.), the free charges will tend to gather in the regions of the fiber where there is less light -- areas of destructive interference of the two modes. This distribution of charges sets up an electric field, which will cause local variations in the refractive index of the fiber. The resulting refractive index grating could "automatically" phasematch the SHG process, which would account for the large conversion efficiencies seen experimentally. Using a few simple fiber modes, the calculation gave promising results, but could not explain all of the observed characteristics. We are presently working on a calculation utilizing exact fiber modes and higher-level photorefractive theory. The resulting overlap integrals and differential equations require numerical integration. We are just now implementing the necessary programs.

Jim Leitch
Progress Report for
AFLGF through UES

APR 1 2 1989

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Charles Adler | Semester: Summer 1989

University: Brown University | Subcontract: S-789-000-026

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

As of the spring semester 1989, I will have completed all course requirements for the Ph.D in physics, and do not expect to have any more coursework.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached report

3. Give brief statement of your involvement with the Avionics Laboratory Laboratory and Mr. Paul McManamon.

The research I have done over the past two semesters has been concerned with the properties of novel ordered and disordered optical systems (colloidal suspensions, crystals; hydroquinone clathrates). There is a good possibilty that the clathrate work (see second report) will tie in directly to Dr. McManomon's work on beam bending and direction switching of lasers.

"I certify that all information stated is correct and complete."

Charles Adler

Signature/Fellowship Recipient

Charles Adler

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Charles Adler is making satisfactory academic progress toward a Ph.D. in the area of Development of E-O Sensor Concepts in the discipline of Physics for the Spring 1989 semester."

Nabil M. Lawandy

Signature/Advising Professor

N.M. Lawandy, Asst. Professor, Engineering

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Charles Adler is making satisfactory academic progress toward a Ph.D. in the area of Development of E-O Sensor Concepts in the discipline of Physics for the Summer 1989 semester."

Walid M. Lawandy

Signature/Advising Professor

N.M. Lawandy, Asst. Professor, Engineering

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Charles L. Adler, studying Development of E-O Sensor Concepts at Brown University.

Give a brief statement of laboratory and/or Dr. Paul McManamon's (fellow's mentor) involvement with Mr. Charles L. Adler.

Mr Adler visited us once before beginning his work. Dr McManamon has had a number of telephone discussions with him since then. Also, Mr Adler has submitted two written reports. His work is basic research that could contribute to non-mechanical beam agility.

26 May 89

Chief Scientist Date

Paul McManamon May 23

Mentor Date

S-789-000-026

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Charles Adler | Semester: Fall 1988

University: Brown University | Subcontract: S-789-000-026

Fellow to complete

1. Courses - Give description of courses a~~nd grades~~ received. (Attach sheet if extra space is needed.)

Research in Physics	A
Colloid and Interface Science	A
Solid State Physics	B
Advanced Quantum Mechanics	B

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached report

3. Give brief statement of your involvement with the Avionics Laboratory Laboratory and Mr. Paul McManamon.

The research I have done over the past two semesters has been concerned with the properties of novel ordered and disordered optical systems (colloidal suspensions, crystals; hydroquinone clathrates). There is a good possibilty that the clathrate work (see second report) will tie in directly to Dr. McManomon's work on beam bending and direction switching of lasers.

"I certify that all information stated is correct and complete."

Charles Adler

Signature/Fellowship Recipient

Charles Adler

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Charles Adler

Semester: Spring 1989

University: Brown University

Subcontract: S-789-000-026

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Research	Pass*
Nuclear/Particle Physics	Pass*
Mathematical Methods of Physics	Pass*

*Expected grades. All courses this semester taken under Pass/Fail (S/NC) option.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached report

3. Give brief statement of your involvement with the Avionics Laboratory Laboratory and Mr. Paul McManamon.

The research I have done over the past two semesters has been concerned with the properties of novel ordered and disordered optical systems (colloidal suspensions, crystals; hydroquinone clathrates). There is a good possibilty that the clathrate work (see second report) will tie in directly to Dr. McManomon's work on beam bending and direction switching of lasers.

"I certify that all information stated is correct and complete."

Charles Adl

Signature/Fellowship Recipient

Charles Adler

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Charles Adler is making satisfactory academic progress toward a Ph.D. in the area of Development of E-O Sensor Concepts in the discipline of Physics for the Fall 1988 semester."

Nabil M. Lawandy

Signature/Advising Professor

N.M. Lawandy, Asst. Professor, Engineering

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

Research and Progress Towards the Ph.D.

In September 1988 I took the qualifying exam for the Ph.D. at Brown. This is a written exam testing knowledge of graduate and undergraduate physics. I passed, receiving the highest grade in my class. In December 1988 I passed the preliminary examination for the Ph.D. This is an oral report on a research topic related to work done as a graduate student. I presented a talk on optical properties of hydroquinone clathrates. I was the first student in my class to pass the prelims. On passing, I became an official candidate for the Ph. D. in physics.

Rather than detailing my research work over the last two semesters on the forms sent, I am enclosing two reports sent to Dr. McManomon. The first was sent in January 1989. The second is being sent concurrently with this report.

Optical Properties of Suspensions of Latex Microspheres

Charles Adler
Department of Physics
Brown University

Summary of Work

In the last semester, I have been engaged in two research projects: the search for Anderson localization of light from the fluorescence from suspensions of polystyrene microspheres, and the investigation of an unexplained color change that occurs in these suspensions.

Submitted to Dr. Paul Mcmanomon, Wright-Patterson AFB, Dayton, OH
January 1989

Localization of Light in Suspensions of Polystyrene Microspheres

Polystyrene microspheres ("polyballs") are small (~1000-10000 Å) charged plastic spheres in aqueous suspension. The charges on the polyballs our group uses come from OSO_3Na groups attached to the polyball surface; in water, $OSO_3Na \rightarrow Na^+ + OSO_3^-$, leaving the sulfate groups attached to the polyball surface. Surface charge density is ~ 1 per 250 $Å^2$, while the cross-sectional area of a sulfate group is ~ 25 $Å^2$.[1] During the past semester, our group has investigated two aspects of the scattering of light from disordered polyball suspensions: the optical analog of Anderson localization, and a peculiar color change associated with the addition of dye to polyball solutions.

The scattering of light from a medium composed of randomly spaced scatterers is a very difficult problem. The best-known application of approximate solutions to this problem is the explanation of the blue sky by the Rayleigh scattering theory. This theory makes one fundamental approximation: the absence of any interference of the scattered light. Interference must be taken into account in any theory when the spacing between particles becomes on the order of the wavelength of the scattered light.

We have investigated the fluorescence from dilute (5×10^{-6} M) solutions of Rhodamine 640 Perchlorate in suspensions of 0.858 μm diameter polystyrene microspheres. The solutions range from .1 to .0001 of initial concentration; that is, from 0.241 balls /μm^3 to 2.41×10^{-5} balls/μm^3. The fluorescence power is seen to rise linearly with concentration (fig. 1) until a point where there is a change in the inflection of the line relating fluorescent power to concentration. We believe this is due to interference effects of the scattered light.

If interference effects are ignored, one can use scattering theory to define a scattering length which is the average distance in the medium which a photon will travel before being scattered. In general, $L = 1/\sigma\rho$, where σ is a scattering cross-section and ρ is the density of scatterers in the medium. A photon undergoing random scattering will in effect undergo a "random walk"; the scattering of light can then be described by a diffusion equation. The time τ a photon spends in the medium is thus cW^2/L, where W is the size of the medium. The fluorescent power is proportional to τ, which in turn is proportional to ρ. This explains the rise in fluorescent power with density of scatterers.

The inflection in the slope of this curve is not so easily explainable. One thought is that there is a "transition" which the medium undergoes from a dielectric to a disordered medium to a dielectric again. For scattering to occur there must be an inhomogeneity in the index of refraction of the medium. Pure water will not scatter light; as the number of polyballs in solution is increased, light is more scattered as the solution is more inhomogeneous. At very high levels of polyball concentration, it can be imagined that the solution starts to look like a dielectric made of *plastic*, with a few scatterers consisting of water. One might intuitively expect that the light scattering would decrease when the concentration was such that there were several balls within one wavelength of each other.

The point of inflection in fig. 1 is thought to be a change in the scattering of the medium where such effects take place. We are currently setting up experiments to send sort (100 psec) pulses through polyball solutions and measuring delay times and pulse spreading to look for localization.

Color Changes in Suspensions of Polystyrene Micrsopsheres

This project started because when mixing solutions of polyballs and dye a color change in the solutions was seen. The solutions changed from a pinkish solution to a blue-purple color over a fairly narrow concentration range. The blue phase has been seen in solutions of 0.079 μm and 0.859 μm diameter polyballs, and we believe that it will occur over a wide range of ball diameters. In the larger balls, the phase was seen at a narrow ball concentration window of ~0.002 balls/μm^3 ; in the smaller, ~0.3 /μm^3 . One curious feature of this phase was that the solution regained its normal pinkish color upon addition of more polyballs.

To investigate these findings, we measured the absorption and fluorescence spectra from the 0.079 nm polyball solutions with 5 μM sulforhodamine and aqueous 5 μM sulforhodamine solutions. The absorption spectra of the two solutions from 300 to 700 nm were taken using a Cary spectrometer. The absorption spectra were very similar in shape, with the peaks in the spectrum of the blue solution shifted about 100 Å into the red from the spectrum of the sulforhodamine solutions . From these curves, we decided to pump at 575 nm when taking the fluorescence spectra (near the peak of the absorption curves) . The fluorescent output was at least an order of magnitude greater from the dye solution than from the dye+ball solution .

To look at the absorption in greater detail, we took the absorption spectrum from 300 to 700 nm of a 0.3 /μm^3 solution of 0.079 μm diameter balls (using the smaller particles to minimize light scattering) with varying concentrations of dye. We compared this to solutions of dye in pure water. Fig. 2 has a plot of the absorption inverse length vs. the dye concentration for both runs. They are seen to be essentially identical. The only change in the absorption is in the position of the absorption maximum (fig. 3). The fluorescence spectra are changed a great deal, which is presumably the reason for the color change of the medium. Fig. 4 shows the fluorescence power as a function of Rhodamine

640 concentration at a fixed polyball density. As is seen, at concentrations of ~ $5x10^{-6}$ molar, the fluorescence power falls by ~10 from the pure rhodamine solutions.

Polyball solutions flocculate very easily, essentially turning into paint. The solutions of 0.858 µm diameter spheres floculated over the course of a few days, sedimenting out on the bottoms of their containers. It was noted that upon flocullation, the dye in solution sedimented out with the polyballs. The solution left behind was much clearer than the rhodamine solutions used as controls; to the eye, it could not be told from pure water. It was also noticed that solutions that were pink, *stayed pink*; solutions that were blue, *stayed blue*, implying that the phenomenon was not dependant on the density of dye or spheres in solution. The flocculation also seemed reversible; shaking the container several times would restore the solution to its original appearance.

This implied very strongly that the rhodamine particles were binding to the polyball surfaces. All densities above the critical blue density seemed to leech the rhodamine out of solution; none of the ones below it seemed to (although it was not known whether those solutions had in fact flocculated). On the assumption that surface effects were leading to the color change, two experiments were tried. In one, we introduced salt into the solutions, hoping to replace the rhodamines attached to the surface of the balls with Na^+ ions. No change in the solution's color was seen to extremely high salt concentrations. In the other, we heated the solutions hoping to drive rhodamines off the surface of the polyballs. Although we heated the solutions to the boiling point of water, again no change was seen. It must be emphasized, however, that these measurements were by inspection *only,* and do not have the sensitivity that the spectrometer could give. It is also possible (in the case of the salt) that insufficient time was given to accomplish any reaction. These experiments will be redone in the future.

Any theory of the color changes in these solutions has to explain why the narrow concentration window exists; that is, why the blue coloration does not persist with the addition of more polyballs to solution. That the rhodamines are actually binding to the ball surfaces is made more plausible by looking at the actual concentrations of the sulfate groups on the polyball surfaces at the critical densities. As mentioned before, there is 1 sulfate group for every 250 $Å^2$ of polyball surface. The critical concentration for the two different polyball sizes used scales inversely with the surface area of each ball type. A simple calculation shows that at the "blue point", the concentration of sulfate groups is very nearly 5×10^{-6} M ; that is, a 1-1 ratio with the rhodamine molecules. In other words, there was monolayer coverage of a polyball at the densities where the maximum color change was seen.

We have speculated that, because there is only a narrow window for the effect to take place in, there is some sort of dye-dye interaction which takes place which is greatly enhanced when the dye molecules are bound to the polyball surfaces. When additional polyballs are added to solution, the effect is diminished as the rhodamines are more spread about on different ball surfaces. We believe that some dye-dye interaction is essential in any model of this phenomenon.

---

[1]Seaman, G. and J.W. Goodwin, "Physicochemical Factors in Latex Rapid Agglutination Tests", *American Clinical Products Review*, June, 1986

Figure 1

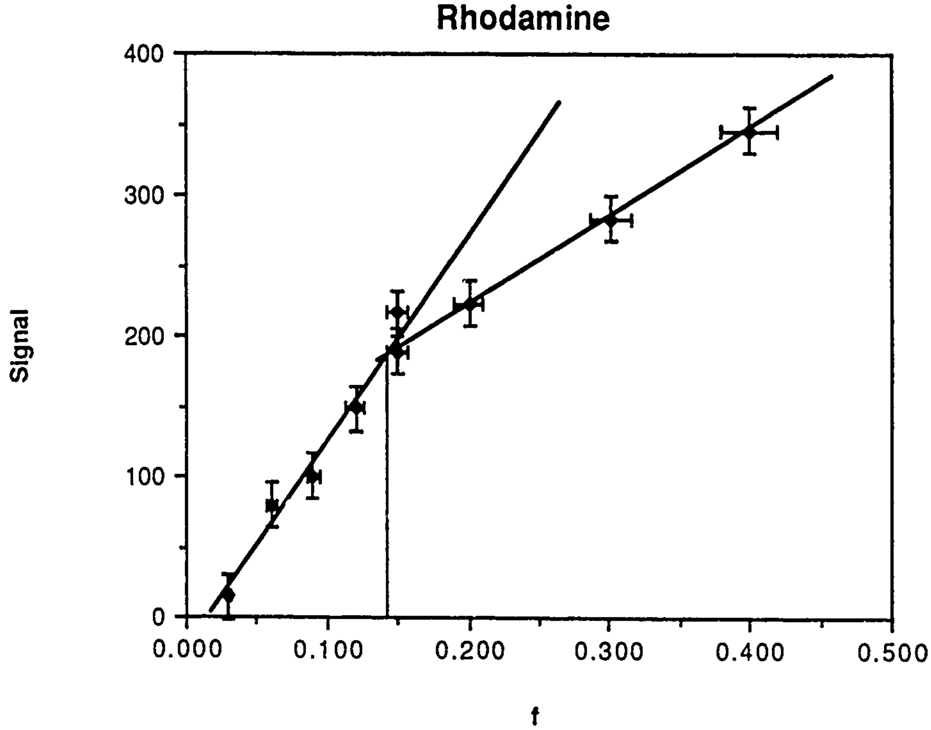
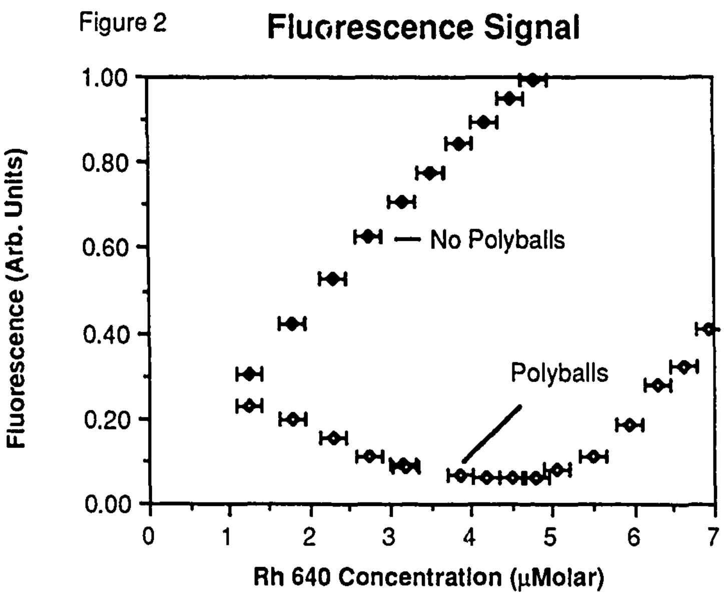

Rhodamine
400
300
200
100
0
Signal
0.000
0.100
0.200
0.300
0.400
0.500
f

Figure 2


Fluorescence Signal
1.00
0.80
0.60
0.40
0.20
0.00
Fluorescence (Arb. Units)
— No Polyballs
Polyballs
0
1
2
3
4
5
6
7
Rh 640 Concentration (μMolar)

Quantum Kerr Effect

Charles Adler
Department of Physics
Brown University
Providence, RI 02912
(401) 863 - 3961

Submitted to Dr. Paul Mcmanomon

The new research I have been involved in this semester which will be continuing through the summer is an investigation of the "quantum Kerr effect", which is a novel source for optical nonlinearities in quantum confined systems such as hydroquinone clathrates. It is shown that torsional motion for an asymmetric molecule can lead to Raman gain, optical generation of quasi-static electric fields, and large nonlinear index of refraction and optically-induced birefringence.

Clathrates are two-component systems consisting of a "host" lattice enclosing "guest" molecules. The guests are not chemically bonded to the host lattice (fig. 1), and are generally not found in stoichiometric ratios. Enclathrated molecules exhibit both torsional and translational modes. The hindered rotation of CO and NO enclathrated in hydroquinone has been studied using far infrared spectroscopy[1], and the torsional frequencies are 85 cm^{-1} (CO) and 33 cm^{-1} (NO).

A simple model for the potential of a diatomic molecule trapped in a crystal is the "hindered-rotational" model developed by Pauling[2]

$$V = V_0\,(1-\cos 2\theta),$$

where θ is the azimuthal angle about the molecule. About $\theta = 0$ the potential can be approximated by $V=V_0\,\theta^2/2$. This defines a torsional frequency of the system

$$\omega_t=\sqrt{\frac{V_0}{I}}$$

where I is the moment of inertia of the molecule. We are interested in the hindered particle as a medium for stimulated Raman scattering. The energy of an asymmetric molecule in an electric field is

$$U = \frac{1}{2}E^2[\alpha_{\parallel}\cos^2(\theta-\theta_0) + \alpha_{\perp}\sin^2(\theta-\theta_0)]$$

where θ is the (small) oscillation about 0, and θ_0 is the angle the field makes with the molecular axis. For θ small this can be expanded out as

$$U \approx \frac{1}{2}E^2[(\alpha_{\parallel}+\alpha_{\perp}) + (\alpha_{\parallel}-\alpha_{\perp})\theta\,\sin(2\theta_0)$$

This implies a polarizability dependant on θ, which is the source of the Raman polarization. Pumping the system with two fields E_1 and E_2 which differ by the torsional frequency leads to Raman gain for E_1 given by[3]

$$g = k_1\frac{\varepsilon_0 N(\alpha_{\parallel}-\alpha_{\perp})^2}{2I\omega_t\gamma}E_2^2$$

where N is the density of rotors and γ is the relaxation time of the molecule. For CO and NO, the Raman gain at 5000 Å is approximately $g \sim (10^{-3}$ cm/Mw$)$ I (I in Mw/cm^2), which is comparable to the Raman gains of most materials[3].

In addition, if the rotors are polar (dipole moment μ) and aligned in the same direction (as in an electret), pumping them with a sharp pulse will rotate them through an angle

$$\delta\theta \approx \frac{(\alpha_{\parallel}-\alpha_{\perp})E^2 \sin 2\theta_0}{4V_0}$$

which will generate a quasi-static electric field given by

$$E_{DC} \approx \frac{\mu N \delta\theta}{\varepsilon_0} = \frac{\mu N(\alpha_{\parallel}-\alpha_{\perp})E^2}{4V_0\varepsilon_0}$$

A model system for the study of this effect is the methanol clathrate. The methanol clathrate is ferroelectrically ordered up to room temperature[4], with a dipole moment of ~3 Debye. Using the formula above, E ~ (0.18 V-cm/MW) I, indicating a roughly 20 mV voltage swing could be induced in a 1 mm sample using a 1 MW/cm^2 pulse.

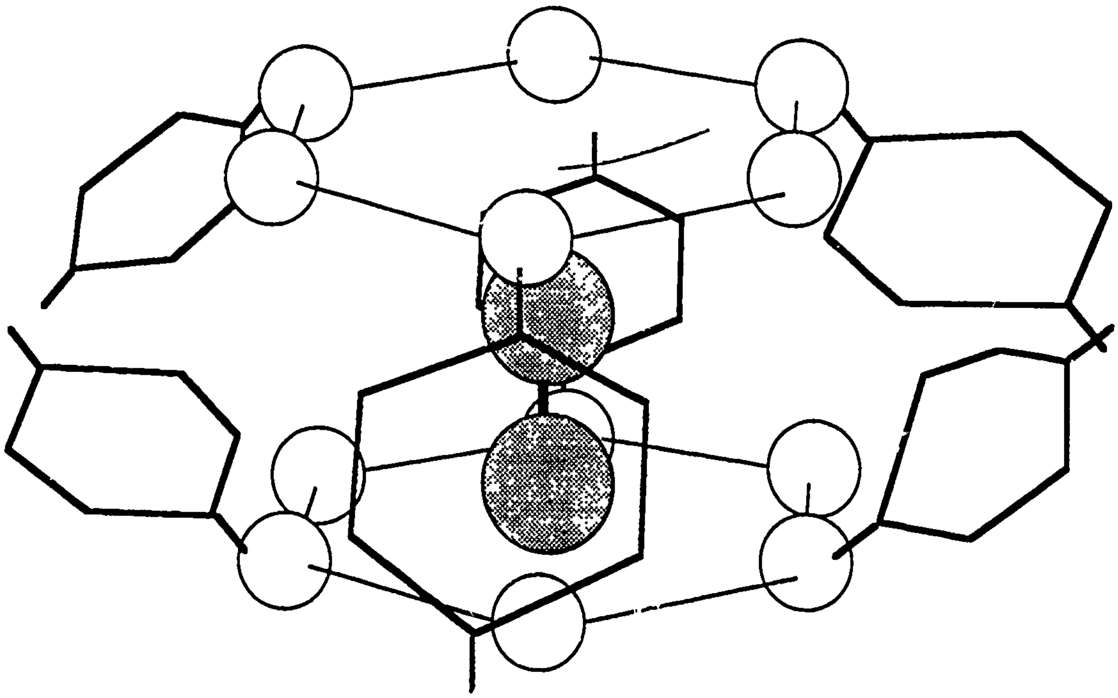
The nonlinear index of refraction due to the quantum Kerr effect can be found most simply by considering the Raman susceptibility for 0 detuning of applied fields. Using the formula for Raman susceptibility given in ref. 3 leads to a predicted nonlinear index of 1.4×10^{-10} I (MW/cm^2) for Methyl Cyanide clathrates, *roughly 10 times higher than that of* CS_2, *currently the material having the highest nonlinear index.*

The above has been submitted to the 1989 QELS conference as a post-deadline talk

References

[1]Burgiel, J.C., H. Meyer, P.L. Richards, *J. Chem. Phys*, 43, 4291 (1965)
[2]Pauling, L., *Phys. Rev.*, **36**, 430 (1930)
[3]Yariv, A., *Quantum Electronics*, pp. 485-487
[4]Mak, T.C.W., *J. Chem. Soc., Perkin Trans.*, **2**, 1435 (1982)

Figure 1



CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Brian R. Bennett, studying Electro-Optics at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. Richard Soref's (fellow's mentor) involvement with Mr. Brian R. Bennett.

The Solid State Sciences Directorate of Rome Air Development Center has an on-going involvement with Mr. Bennett in the area of his Doctoral research. Dr. Richard Soref at RADC/ESOC has collaborated with Mr. Bennett on carrier-induced bandfilling and bandgap shrinkage in GaAs, InP, and InGaAsP. The paper was submitted to the Journal of Quantum Electronics. Dr. Soref is mentoring Mr. Bennett's progress in spectroscopic ellipsometry of strained InGaAs and InP-on-Si, and his work on low temperature oxide growth.

Richard A. Soref 12 May

Chief Scientist Date

Mentor Date

S-789-000-027

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Brian Bennett   Semester/Academic Term: Spring 1989

University: Massachusetts of Technology   Subcontract: S-789-000-027

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

3.21	Kinetic Processes in Materials	B
3.475	Compound Semiconductors	Listener
6.732	Physics of Solids II	Listener

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Completed theoretical work on the influence of free-carriers on the refractive index of III-V semiconductors.

Continued to characterize III-V semiconductor epitaxial layers using ellipsometry; submitted abstract to Materials Research Society meeting (Boston, November 1989).

3. Give brief statement of your involvement with the Rome Air Development Laboratory and Dr. Richard Soref. Also list any items of interest such as academic awards, publications, other information that can be used for a LGFP newsletter.

I collaborated with scientists at the Rome Air Development Center on three projects during the academic year. The resulting publications are:
(continued on attached page)

"I certify that all information stated is correct and complete."

Brian R. Bennett
Signature/Fellowship Recipient

Brian R. Bennett
TYPED NAME/FELLOWSHIP RECIPIENT

3. Continued

B. R. Bennett, R. A. Soref, and J. A. del Alamo, "Carrier-Induced Change in Refractive Index of InP, GaAs, and InGaAsP," IEEE Journal of Quantum Electronics, QE-25, to be published in Nov. or Dec., 1989.

K. Vaccaro, B. R. Bennett, J. P. Lorenzo, A. Davis, and H. G. Lipson, "MIS Structures on InP Using Oxides Deposited Near 100°C," SPIE Proc. 1144, 1989.

R. A. Soref and B. R. Bennett, "Carrier Refraction in Quantum-Well Waveguides," Applied Optics, 28, 01 Sept 1989.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Brian Bennett is making satisfactory academic progress toward a Ph.D. in the area of Electro-Optics for the Spring 1989 academic term."

David A Rudman

Signature/Advising Professor

David A. Rudman
Pirelli Associate Professor
of Electronic Materials

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Brian R. Bennett Semester: Fall 1988

University: Massachusetts Institute of Technology Subcontract: S-789-000-027

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

3.20 Thermodynamics of Materials............................ A
3.43 Chemistry and Physics of Materials .... A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Gave talk entitled, "Bandfilling Electro-optic Effect in InP and GaAs," at SPIE meeting, September, 1988

Worked to develop method to optically characterize mis-matched III-V semiconductor epitaxial layers using ellipsometry

Continued research on low-temperature deposition of silicon dioxide

"I certify that all information stated is correct and complete."

Brian R. Bennett
Signature/Fellowship Recipient

Brian R. Bennett
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5014C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Brian R. Bennett is making satisfactory academic progress toward a Ph.D. in the area of Electro-Optics in the discipline of Materials Science for the Fall 1988 semester."

David A. Rudman

Signature/Advising Professor

David A. Rudman, Assoc. Prof. of Electr. Mat.

TYPED NAME/TITLE OF ADVISING PROFESSOR

5014C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Lawrence Bentley

Semester: Summer 1989

University: Princeton University

Subcontract: S-789-000-028

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

No courses taken this summer.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See Attachment 1

3. Give brief statement of your involvement with the Engineering and Service Center Laboratory and Dr. Cornette.

Maintained telephone and written correspondence including sending preprints of current work.

"I certify that all information stated is correct and complete."

Lawrence R. Bentley

Signature/Fellowship Recipient

Lawrence R Bentley

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

ATTACHMENT 1 -- LAURENCE R. BENTLEY

RESEARCH PROGRESS - September 15, 1989

A paper entitled "Fourier analysis of the Eulerian-Lagrangian Least Squares Collocation Method" was completed, and it was submitted to the INTERNATIONAL JOURNAL OF NUMERICAL METHODS IN FLUIDS.

The ELLESCO transport solver requires a fluid velocity field in order to track collocation points. The summer's work has been aimed at writing a computer program that solves the groundwater flow equation. Since the generation of an accurate velocity field is the main goal, a mixed finite element formulation is used. That is, fluid fluxes in the x and y directions as well as the hydraulic head are kept as state variables. In addition, least squares are used to generate the algebraic system of equations that will be solved. A preconditionned conjugate gradient solver with compact data storage is used. The two-dimensional confined case has been coded. Presently work continues on implementing grid refinement, irregular domain boundaries, and the unconfined aquifer case.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Lawrence Bentley is making satisfactory academic progress toward a Ph.D. in the area of Subsurface Flow and Transport in the discipline of Civil Engineering for the Summer 1989 semester."

George F. Pinder
Signature/Advising Professor

DR. GEORGE F. PINDER
TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Engineering and Services Center requests the continuation of the AFOSR fellowship for Mr. Laurence Bentley, studying Subsurface Fate and Transportation of Pollutants at Princeton University.

Give a brief statement of laboratory and/or Dr. Jimmy C. Cornette (fellow's mentor) involvement with Mr. Laurence Bentley.

Chief Scientist	Date	Mentor	Date

S-789-000-028

CONCURRENCE FORM

The Engineering Science Center requests the continuation of the AFOSR fellowship for Mr. Laurence R. Bentley, studying Subsurface Fate and Transportation of Pollutants at Princeton University.

Give a brief statement of laboratory and/or Dr. Jimmy Cornette's (fellow's mentor) involvement with Mr. Laurence R. Bentley.

Mr Bently's studies are proceeding satisfactorily and he has established ties with some of the researchers at HQ AFESC. Additionally, Mr Bentley traveled to HQ AFESC and presented a seminar on his research to the technical staff.

Daniel A. Stone 22 Mar 89
Chief Scientist Date

Jimmy Cornette 21 Mar 89
Mentor Date

S-789-000-028

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Laurence Bentley   Semester: Spring 1989

University: Princeton University   Subcontract: S-789-000-028

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

No courses were taken this term, but all course requirements and general examination have already been succesfully completed.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

SEE ATTACHMENT 1.

3. Give brief statement of your involvement with the Engineering and Service Center Laboratory and Dr. Cornette.

Maintained telephonic contact with Dr. Cornette. We have discussed my research and research progress as well as present status and possible future directions of computer modelling of contamin transport.

"I certify that all information stated is correct and complete."

Laurence R. Bentley
Signature/Fellowship Recipient

LAURENCE R. BENTLEY
TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. La~~w~~urence Bentley is making satisfactory academic progress toward a Ph.D. in the area of Subsurface Flow and Transport in the discipline of Civil Engineering for the Spring 1989 semester."

George F Pinder

Signature/Advising Professor

DR. GEORGE F. PINDER

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

ATTACHMENT 1 -- LAURENCE R. BENTLEY

RESEARCH PROGRESS - June 5, 1989

During the spring semester, comparisons of ELLESCO results with the results of two industrial Eulerian-Lagrangian computer codes were completed. The conclusion was that the ELLESCO method obtained comparable accuracies with twice the grid spacing.

Implementation of the Sheidigger approximation of dispersion was completed. In this approximation, dispersion is a linear function of velocity. The implementation of point sources, such as an injection well was also completed.

Fourier analysis of the ELLESCO solution of the one dimensional constant diffusion coefficient transport equation was completed. A paper entitled "Fourier analysis of the Eulerian-Lagrangian Least Squares Collocation Method" is now in preparation.

Mr. Rodney Darrah June 6, 1989

Universal Energy Systems, Inc.

4401 Dayton-Xenia Road

Dayton, Oh 45432

Dear Mr. Darrah,

Please find enclosed the original and one copy of my "Certification of Academic Progress" for Spring, 1989. Please forward the copy to the Contracts Department

Sincerely Yours,

Laurence R. Bentley

Department of Civil Engineering

Princeton University

Princeton, New Jersey 08544

cc Contracts Department

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Laurence Bentley

Semester: Spring 1989

University: Princeton University

Subcontract: S-789-000-028

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   No coarses were taken this term, but all coarse requirements and general examination have already been succesfully completed.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   SEE ATTACHMENT 1.

3. Give brief statement of your involvement with the Engineering and Service Center Laboratory and Dr. Cornette.

   Maintained telephonic contact with Dr. Cornette. We have discussed my research and research progress as well as present status and possibl future directions of computer modelling of contamin transport

"I certify that all information stated is correct and complete."

Laurence R. Bentley
Signature/Fellowship Recipient

LAURENCE R. BENTLEY
TYPED NAME/FELLOWSHIP RECIPIENT

20916

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. La~~w~~urence Bentley is making satisfactory academic progress toward a Ph.D. in the area of Subsurface Flow and Transport in the discipline of Civil Engineering for the Spring 1989 semester."

George F Pinder
Signature/Advising Professor

DR. GEORGE F. PINDER
TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

ATTACHMENT 1 -- LAURENCE R. BENTLEY

RESEARCH PROGRESS - June 5, 1989

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Implementation of the Sheidigger approximation of dispersion was completed. In this approximation, dispersion is a linear function of velocity. The implementation of point sources, such as an injection well was also completed.

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Mr. Rodney Darrah June 6, 1989

Universal Energy Systems, Inc.

4401 Dayton-Xenia Road

Dayton, Oh 45432

Dear Mr. Darrah,

Please find enclosed the original and one copy of my "Certification of Academic Progress" for Spring, 1989. Please forward the copy to the Contracts Department

Sincerely Yours,

Laurence R. Bentley

Laurence R. Bentley

Department of Civil Engineering

Princeton University

Princeton, New Jersey 08544

cc Contracts Department

CONCURRENCE FORM

The Flight Dynamics Laboratory requests the continuation of the AFOSR fellowship for Mr Daniel R. Bower, studying Hypersonic Boundary Layer Transition at the State University of New York at Buffalo.

Give a brief statement of laboratory and/or Mr K. Stetson's (fellow's mentor) involvement with Mr Daniel R. Bower.

Mr Bower made a visit to WRDC/FIMG for technical discussions with Mr Stetson and other laboratory personnel.

Mr Stetson suggested to Mr Bower that a NASA/LaRC workshop on boundary-layer transition during the week of 29 May 1989 would be a worthwhile meeting to attend. Mr Bower subsequently made arrangements with his University to attend and, since Mr Stetson was participating in this workshop, this provided opportunity for many discussions.

The AIAA 20th Fluid Dynamics Conference was held at Buffalo, NY on 12-14 June 1989. Mr Stetson participated in a boundary-layer transition workshop and a technical session on transition. Mr Bower attended both of these events and this provided additional opportunity for technical discussions.

In summary, the interaction between WRDC/FIMG and Mr Bower has been excellent.

26 Jun '89 — Chief Scientist, Date

Kenneth F. Stetson 19 JUNE 89 — Mentor, Date

S-789-000-029

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Daniel R. Bower

Semester: Spring 1989

University: State University of New York at Buffalo

Subcontract: S-789-000-029

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

MEA 546 Heat Transfer II (3 Hrs.)
Instructor: Dr. C. P. Yu

Forced convection: governing equations, general formulation of similarity analysis, flow and heta transfer in tubes, boundary layer theory, heat transfer in external flows, temperature dependent solutions, and high speed applications. Natural convection: Boussinesq and other approximations, boundary region equations, similar and near similar solutions, horizontal and regimes. Condensation and boiling.

Grade received: A

MEA 519 Turbulent Flow I (3 Hrs)
Instructor: Dr. W. K. George

The statistical and phenomenological theories of turbulence and turbulence transport are outlined; correlation functions, spectral functions, decay laws; semi-empirical theories of turbulence. Deterministic non-

2. **Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)**

During the spring 89 semester, work continued on the first phase of the hypersonic transition research program, which was outlined in the previous progress report. In addition to this transition work, a joint research paper was produced with Dr. W. K. George in the related area of turbulent boundary layers.

Transition Research

As describedpreviously, the first phase of the hypersonic transition research program consists of measuring the freestream disturbance environment. Several measurements of fluctuating pressure in the CALSPAN 96" (con't)

"I certify that all information stated is correct and complete."

Daniel R. Bower

Signature/Fellowship Recipient

Daniel R. Bower

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5017C

1. (continued)

periodic behavior; chaos.

Grade received: I

MEA 699 Supervised Research (6 Hrs)
Instructor: Dr. W. K. George

See # 2.

Grade received: L (continuing work)

Semester GPA: 4.00/4.00
Overall GPA: 3.767/4.00

2. (continued)
hypersonic shock tunnel at Mach 8, $Re/ft=4.0x10^6$ were made at the end of the fall 88 semester. During the spring 89 semester reduction of the database compiled from these tests was initiated. This consists of digitizing and converting the data to a form suitable for analysis and graphical representation. Fourier transforms of all the data was performed to convert the data from time space to frequency space. In addition, a survey of recent work in hypersoni boundary stability was performed and a paper was presented[1] relating the recent work to the present study.

Related Research

Also during this time period, an analytical study was performed by Dr. W. K. George and Mr. Bower in the area of turbulent boundary layers. This study re-examines from an analytical viewpoint the validity of the power law for incompressible, zero pressure gradient turbulent boundary layers and formulated a 'new' power law, and compared this law with the log law for several classic experiments. Results of this study are to be presented at the Third Joint ASCE/ASME Mechanics and Fluid Enginnering Conference. Further sutdies of the 'new' power law are planned, studying the application of this law to other types of turbulent flow, including supersonic/hypersonic boundary layers.

Referances:

1.) D. R. Bower, "Unsteady Disturbances in Hypersonic Boundary Layers", Paper presented at the Sixth Annual Iroquois Fluids Conference, Casawasco Conference Center, Lake Owasco, NY, March 17-19 1989.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Daniel R. Bower is making satisfactory academic progress toward a Ph.D. in the area of Hypersonic Boundary Layer Transion in the discipline of Aerospace Engineering for the Spring 1989 semester."

William K. George

Signature/Advising Professor

Dr. William K. George

TYPED NAME/TITLE OF ADVISING PROFESSOR

5017C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Daniel R. Bower

Semester: Fall 1988

University: State University of New York at Buffalo

Subcontract: S-789-000-029

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

MEA 545 Heat Transfer 1 (3 Hrs.)
Instructor: Dr. J. D. Felske

Theory of conduction and conduction equations; steady-state solutions, trai solutions, moving boundary problems, transform techniques, integral approximati numerical methods for time dependent and independent problems.

Grade received: A-

MEA 638 Higher Approximate Methods in Fluid Mechanics (3 Hrs.)
Instructor: Dr. C. S. Liu

Regular and singular pertubation problems, techniques of pertubation theor Method of matched asymptotic expansions; method of strained coordinates; Large Reynolds number flow; WKB method. Inviscid singular perturbation problems.

Grade received: A

(continued)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the fall 88 semester, the first phase of the hypersonic transition research program was initiated. The first phase consists of measuring the frees disturbance environment and determiningthe frequency content of these disturbanc for it is these disturbances which amplify and lead to boundary layer transition The emphasis of this period's work was not only to measure typical wind tunnel freestream disturbances, but to also develop instrumentation and methodologies which may be employed in future wind tunnel transition tests.

Instrumentation and Test Facilities

A pitot pressure rake was designed and fabricated to allow multipoint measur

(continued)

"I certify that all information stated is correct and complete."

Daniel R. Bower

Signature/Fellowship Recipient

Daniel R. Bower

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5017C

1. (continued)

MEA 699 Supervised Research (6 Hrs.)
Instructor: Dr. W. K. George

See #2.

Grade received: L (continuing work)

Semester GPA: 3.835/4.00

Overall GPA: 3.741/4.00

2. (continued)

ments of fluctuating pressur in the wind tunnel. The rake was designed such that it be attached to a model in the test section of the wind tunnel facilities, and hence may be used in conjuction with transition tests on several model configurations.

The pressure rake has eight positions from which fluctuating pressures may be measured. These measurement positions are at relative distances to each other such that cross-correlation analysis techniques may be used. For the present tests, the positions are instrumanted with Kulite piezoelectric pressure transducers such that the measuring surface of the gage is directly exposed to the freestream, hence measuring total pressure and the fluctuations of total pressure.

In the first series of wind tunnel tests, the rake was mounted on a 6 deg sharp cone in the CALSPAN 96 inch hypersonic shock tunnel (with 'A' nozzle). A shock mounting pad was also designed to damp any vibrations of the rake and to insulate the rake from any vibrations of the model. The shock mounting pad was also designed such that the frequency of any vibrations of the rake would be known. The test conditions for the first series are Mach 8, Re/ft= 4.0×10^6.

Future Work

At the end of the fall 88 semester, data from several tests were collected. During the spring 88 semester, the data obtained from these tests will be analyzed.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Daniel R. Bower is making satisfactory academic progress toward a Ph.D. in the area of Hypersonic Boundary Layer Transion in the discipline of Aerospace Engineering for the Fall 1988 semester."

William K. George

Signature/Advising Professor

Dr. William K. George

TYPED NAME/TITLE OF ADVISING PROFESSOR

5017C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Leslie I. Brown

Quarter: Summer 1989

University: Stanford University

Subcontract: S-789-000-030

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Grade
Digital Signal Processing	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Still working on Master's Degree.

"I certify that all information stated is correct and complete."

Leslie I. Brown
Signature/Fellowship Recipient

Leslie I. Brown
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5018C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Leslie I. Brown is making satisfactory academic progress toward a Ph.D. in the area of Electrical Engineering/Signal Processing in the discipline of Electrical Engineering for the Summer 1989 quarter."

Dwight G. Nishimura

Signature/Advising Professor

DWIGHT G. NISHIMURA, Act. Asst. Prof.

TYPED NAME/TITLE OF ADVISING PROFESSOR

5018C

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Ms. Leslie I. Brown, studying Electrical Engineering/Signal Processing at Stanford University.

Give a brief statement of laboratory and/or ~~Dr~~ Mr. Richard L. McKinley's (fellow's mentor) involvement with Ms. Leslie I. Brown.

No contact during this reporting period. Grades & courses are acceptable

Billy E. Welch

Chief Scientist Date

BILLY WELCH 12 MAY 1989
HQ HSD/CA
Brooks AFB TX 78235-5000

Richard L. McKinley

Mentor Date

RICHARD MCKINLEY 25 MAY 198
AAMRL/BBA
WPAFB OH 45433-6573

S-789-000-030

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Leslie I. Brown — Quarter: Spring 1989

University: Stanford University — Subcontract: S-789-000-030

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Grade
Information Systems Seminar	Pass
Medical Imaging Systems	A+
Intro. to Linear Systems	A-
Elec. Engr. Seminar	Pass
Electromagnetic Waves	B
Modern Dance I	Pass
Adv. Beg. Swimming	Pass

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Currently working on Master's Degree

"I certify that all information stated is correct and complete."

Leslie I. Brown

Signature/Fellowship Recipient

Leslie I. Brown

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5018C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Leslie I. Brown is making satisfactory academic progress toward a Ph.D. in the area of Electrical Engineering/Signal Processing in the discipline of Electrical Engineering for the Spring 1989 quarter."

Dwight Nishimura

Signature/Advising Professor

Dwight G. Nishimura

TYPED NAME/TITLE OF ADVISING PROFESSOR

5018C

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Ms. Leslie I. Brown, studying Electrical Engineering/Signal Processing at Stanford University.

Give a brief statement of laboratory and/or Dr. Richard L. McKinley's (fellow's mentor) involvement with Ms. Leslie I. Brown.

Ms. Brown and I have met and discussed areas of research that are of joint interest to Ms Brown and the laboratory. Ms Brown has been given a briefing on the mission of the laboratory and current research projects. She also was given a tour of the facilities. An invitation has been extended to Ms. Brown to come to the laboratory during the summer.

B. E. Welch 6 Mar 89

Chief Scientist Date

Richard L. McKinley 28 Feb

Mentor Date

RICHARD MCKINLEY
AAMRL/BBA
WPAFB OH 45433-6573

S-789-000-030

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Leslie I. Brown Quarter: Winter 1989

University: Stanford University Subcontract: S-789-000-030

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Grade
Matrix Theory and Applications II	A
Magnetic Resonance Imaging Seminar	A
Fourier Optics	B
Entreprenurial Engineer Seminar	Pass
Electrical Engineering Seminar	Pass
Electromagnetics Fundamentals	B
Jazz Dance II	Pass

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Currently working on master's degree, no research as of yet.

"I certify that all information stated is correct and complete."

Leslie I. Brown
Signature/Fellowship Recipient

Leslie I. Brown
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5018C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Leslie I. Brown is making satisfactory academic progress toward a Ph.D. in the area of Electrical Engineering/Signal Processing in the discipline of Electrical Engineering for the Winter 1989 quarter."

Dwight Nishimura

Signature/Advising Professor

Dwight G. Nishimura
Acting Asst. Professor

TYPED NAME/TITLE OF ADVISING PROFESSOR

5018C

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. John G. Bruno, studying Microbiology/Immunology at University of Arizona.

Give a brief statement of laboratory and/or Dr. J. L. Kiel's (fellow's mentor) involvement with Mr. John G. Bruno.

Dr J.L. Kiel has worked with Mr Bruno on a summer project (1989) at the School of Aerospace Medicine and has spoken with Dr Olson (Mr Bruno's graduate adviser) about future collaboration.

George Chuoke 28 Jul 89

Chief Scientist Date

Johnathan L. Kiel 26 Jul 89

Mentor Date

S-789-000-031

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John G. Bruno

University: The University of Arizona Subcontract: S-789-000-031

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

		Grade
Fall 1988:		
Eukaryotic DNA Replication	RONC (Micro)505X	B
Spring 1989:		
Nucleic Acids MCB 568A		B
Microbiology Research Seminar 696		A

Other units in each semester have consisted of Dissertation and Research credits

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

In the past year I have completed a project involving the use of digital image processing (DIP) to discriminate human peripheral blood lymphocytes cultured at extremely low (10^{-13} to 10^{-15} M) concentrations of the T-cell mitogen, Concanavali (Con A) from human peripheral lymphocytes cultured at much higher concentrations

"I certify that all information stated is correct and complete."

John G. Bruno 6/22/89

Signature/Fellowship Recipient

John G. Bruno

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. John G. Bruno is making satisfactory academic progress toward a Ph.D. in the area of Microbiology/Immunology in the discipline of Microbiology for the Spring 1989 semester."

George B. Olson

Signature/Advising Professor

✓

Dr. George B. Olson

TYPED NAME/TITLE OF ADVISING PROFESSOR , Immunology

LLD/sdp 4680C

Con A (10^{-7} to 10^{-9}M). Some DIP features were found which were concentration-dependent, while others were not concentration-dependent. Also, some DIP feature could be used to distinguish the chromatin of blast cells from non-blast cells, while other features could not. This project was presented in the form of an abstract and poster at the 1989 FASEB Meeting in New Orleans, LA.

Work has been on going toward finding DIP features that can be used to discriminate early stages of HL-60 granulocytic differentiation from monocytic differentiation. It appears that such discriminatory features do emerge within the first hours of induction, before the human eye can distinguish two morpholog different cell types. This finding may represent the discovery of two distinct nuclear conformations induced by changes in nuclear matrix proteins such as histo lamins, etc. This proposed project constitutes the basis of my dissertation and is being submitted to my committee in August 1989 at which time I will be allowed to take the oral Ph.D. examination.

I am currently performing research on the chemiluminescence of HL-60 cell types under the guidance of Dr. Johnathan Kiel at Brooks AFB in San Antonio Texas.

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. John G. Bruno, studying Microbiology/Immunology at University of Arizona.

Give a brief statement of laboratory and/or Dr. J. L. Kiel's (fellow's mentor) involvement with Mr. John G. Bruno.

Mr Bruno's work appears relevant and scientifically sound. After a hiatus in contact between the fellow and mentor, a telephone conversation (9 Mar 89) between them has revealed that Mr Bruno with the consent of his major advisor will do research at the USAF School of Aerospace Medicine this summer (1989). Mr Bruno will be encouraged to acknowledge Air Force sponsorship on all his abstracts and publications.

20 Mar 89		15 March 1989	
Chief Scientist	Date	Mentor	Date

S-789-000-031

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. John G. Bruno

University: The University of Arizona Subcontract: S-789-000-031

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   See attached sheet.

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   See attached sheet.

"I certify that all information stated is correct and complete."

John G. Bruno

Signature/Fellowship Recipient

John G. Bruno

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. John G. Bruno is making satisfactory academic progress toward a Ph.D. in the area of Microbiology/Immunology in the discipline of Microbiology for the Fall 1988 semester."

George B. Olson

Signature/Advising Professor

George B. Olson, Ph.D.

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4680C

1. Courses

Courses	Units	Grade
Micribio. 505X Eukaryotic DNA Replication	3	B
Microbio. 560 Structure and Function of Immunoglbulins	3	A
Microbio. 630 Immunology of Infectious Disease	4	A
Microbio. 695A Read Micro./Immunology	4x1	A
Microbio. 900 Research	2	S (Satisfactory)
Microbio. 920 Dissertation	9	K (Continuing)

2. Description of research and progress toward dissertation

Research during the Summer and Fall of]988 has centered on two projects. First was a digital image processing (DIP) study of chromatin features of Feulgen stained human peripheral blood lymphocytes (PBLs) stimulated at very low (10^{-16}M to 10^{-13}M) levels of Concanavalin A versus lymphocytes transformed at more conventional Con A concentrations of 10^{-6}M to (see attached abstract forms). DIP of these lymphocytes sensitive to low and high levels of Con A showed the two blast cells could be differentiated on the basis of nuclear area, total optical density and a Markovian textural feature measuring the correlation of pixel O.D. values along any given nuclear diamete Other global and Markovian features may simply be used to separate blast from nonblast cells. Some DIP features show a positive correlation with the concen tion of Con A used in culture, while others show a negative correlation with concentration of Con A, and still others show zero correlation. Some DIP featı show no usefulness in differentiating blast from nonblast cells and do not help in distinguishing blast cells grown in various concentrations of Con A. These studies will be presented in poster form at the 1989 Federation of Americ Scientists for Experimental Biology (FASEB) meeting in New Orleans, LA., March 19-23.

The second major area of reaserch progess related to my dissertation deals with the use of DIP to characterize and identify populations of HL-60 promyelo-monocytic leukemia cells induced to differentiate along the granulocytic or monocytic pathways by use of retinoic acid, bromodeoxyuridine (BrdU), dimethyl sulfoxide (DMSO), or TPA (a phorbol ester).

In addition, work is proceeding toward the use of DIP in prediction of whi pathway the bipotent HL-60 stem cells will take, based on subvisual chromatin patterns, when induced by BrdU, since BrdU induction produces both granulocytic and monocytic differentiation. Surface antigens characteristic of early or developing cells along either pathway (i.e.- HLA-DR and CD-16) might be used tc rosette with antibody conjugated latex microbeads and thus allow for simultaneo nuclear (Feulgen) staining and DIP of transforming cells along either pathway. Data generated from such DIP analyses might prove useful in early prediction of resultant cell types under any number of environmental influences or insults This work might ultimately have implications in the early detection of cells destined for cancerous transformation or in the evaluation of effects of chemotherapeutic agents on cellular fate.

ABSTRACT MUST BE RECEIVED AT SOCIETY OFFICE BY TUESDAY, NOVEMBER 1, 1988.

Mail to your Society of membership (APS, ASPET, AAP, AIN/ASCN, AAI)
ASBMB and CIS members send to AAI
ASCB members send to ASPET
BMES and SEBM members send to APS

9650 Rockville Pike
Bethesda, MD 20814

1989 FASEB ABSTRACT FORM

DO NOT FOLD THIS FORM

MAILING ADDRESS OF FIRST AUTHOR
(Please Print in black ink or type. Provide full name rather than initials.)

Mr John G. Bruno
Dept Micro & Immunol.
Univ. of Arizona
Tucson, Az 85721

Phone: Office ~~602-621-4880~~
Home/Holiday ______

PRESENTATION PREFERENCE (Check one)

☐ Oral ☒ Poster ☐ Indifferent

Final decision regarding presentation format is at the discretion of the programing society.

SELECT CATEGORY NUMBERS & TITLES
(See Minisymposium and Topic Category Lists)

1. 624-4 Computer Image Analysis
2. 627-4 Lymphocytes
3. ______ ______

Is first author graduate student? ☒ Yes ☐ No

IMPORTANT

1. Prepare abstract carefully, on this form only.
2. Also fill out:
   a. Topic category selection
   b. Mailing address of first author
   c. Signature block for member's signature
3. Return to your society of membership by November 1, 1988.
   a. The original typed abstract form
   b. Two photocopies
   c. Abstract handling fee
   d. Program confirmation card
4. See over for complete instructions.

REMITTANCE (NONREFUNDABLE)
ABSTRACT HANDLING FEE $25

QUANTITATION OF CONCENTRATION DEPENDENT FEATURES (CDFs) IN MITOGEN INDUCED TRANSFORMATION OF HUMAN PERIPHERAL BLOOD LYMPHOCYTES (PBLs).

J.G. BRUNO & GEORGE B. OLSON. DEPT. MICRO & IMMUNO. UNIVERSITY OF ARIZONA, TUCSON, AZ 85721

Ligands of known psychoneuroimmune functions react with r tors over a range of 10^{-7} to 10^{-16}M to yield a diphasic r sponse as measured by chemotaxis, cytotoxicity, electroph esis and stimulation indecies. Most studies utilize liga at conc of 10^{-9} to 10^{-6}M. We initiated studies to quanti the Con-A induced transformation of PBLs and compare the global and chromatin features of transformed blast cells (BCs) by digitized morphometric measurements (DMM). Con-A at 10^{-15} to 10^{-13}M yields 10-15% BCs and 80-90% at 10^{-9} t 10^{-7}M. This confirms earlier studies and the existence o a small population of Con-A sensitive cells as well as ce which respond to the > Con-A conc. Data indicate the existence of CDFs indicative of transformation, non-CDFs which differentiate BCs and non-BCs, and non-CDFs which d not separate BCs and non-BCs. BCs of the 10^{-9} to 10^{-6}M group are classified from the 10^{-15} to 10^{-13}M group by > size, > total optical density (OD) and a correlation feat for distribution of OD points along any vector. Data suggest DMM of subvisual textural features will identify of value for detection & evaluation of mitogen induced transformation. (Spon. by Eleanor Naylor Dana Charitable Trust).

Blue lines are printer's cut lines; do not type on or outside of these lines

All compounds that are designated by code or initial letters in the title must be ide adequately in the abstract, e.g., MJ-1999; 4-(2-isopropylamino-1-hydroxyethyl) metha fonanilide hydrochloride.

All investigators must adhere to the guidelines as listed on the reverse of the abstract f

APS, BMES, SEBM, ASPET & AIN/ASCN members only:
Signing member, are you willing to chair a session? ☐ Yes, category # ______

APS, AAP & AIN/ASCN members only:
☐ Submitted for special Society student or training award. Type of award ______

MEMBER'S AFFILIATION (Check one only):
☐ APS ☐ ASBMB ☐ ASPET ☐ AAP ☐ AIN ☐ ASCN ☒ AAI ☐ ASCB ☐ BMES ☐ SEBM

Submission of signed form indicates acceptance of rules including final withdrawal date of November 2 No exceptions will be made.

GEORGE B. OLSON
Member's Name (Print or type)

George B. Olson
Member's Signature

(602) 621-4880
Member's Phone

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Ms. Joan E. Carletta, studying Microcircuit Testability at Cornell University.

Give a brief statement of laboratory and/or Dr. Warren Debany's (fellow's mentor) involvement with Ms. Joan E. Carletta.

Since the last evaluation of Ms. Carletta's progress, contact has been maintained by means of netmail. She has discussed her current work in reducing computational errors in systolic arrays used for signal processing. She will give a presentation on the work that she and her Academic Advisor have accomplished at a SIAM Annual Meeting in San Diego in July.

Fred Diamond 18 Jul 89 | WARREN H. DEBANY, Ph.D. 7/14/89

Chief Scientist Date | Mentor Date

S-789-000-032

CERTIFICATION OF ACADEMIC PROGRESS

RECEIVED JUN 2 ? 198?

Fellow: Ms. Joan E. Carletta

Semester: Spring 1989

University: Cornell University

Subcontract: S-789-000-032

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Electrical Engineering 542, Parallel Processing, Grade of A-.

Electrical Engineering 644, Fault-Tolerant Computing, Grade of A-.

Mathematics 432, Introduction to Algebra II, Grade of A.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I have begun a study of algorithm-based fault tolerance schemes, especially those used to locate and correct transient errors in multiprocessor arrays. Using the Matlab software package on a SUN workstation, I have written routines to simulate the checksum approach for fault tolerance of matrix operations. I am studying the effects of floating point roundoff errors on this approach.

"I certify that all information stated is correct and complete."

Joan E. Carletta

Signature/Fellowship Recipient

Joan E. Carletta

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5019C

RECEIVED JUN 2 ? 1989

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Joan E. Carletta is making satisfactory academic progress toward a Ph.D. in the area of Microcircuit Testability in the discipline of Electrical Engineering for the Spring 1989 semester."

Franklin Luk
Signature/Advising Professor

Dr. Franklin T. Luk
TYPED NAME/TITLE OF ADVISING PROFESSOR

5019C

THE GRADUATE SCHOOL
Cornell University
SAGE GRADUATE CENTER
ITHACA, NEW YORK 14853-6201

June 21, 1989

Mr. Rodney Darrah
Program Manager
Laboratory Graduate Fellowship Program
Universal Energy Systems, Inc.
4401 Dayton-Xenia Road
Dayton, OH 45432-1894

Dear Mr. Darrah:

I am enclosing the Spring 1989 Progress Report Forms for Ms. Joan Carletta. It is my understanding that a statement of progress must be filed with you for those students who are receiving a Universal Energy Systems Fellowship.

I hope that all of the necessary paperwork is in order. Please do not hesitate to contact me should you require further information.

Sincerely yours,

Joanne Bordonaro

Joanne Bordonaro
Director
Graduate Fellowship and
Financial Aid Office

JSB:klc
Enclosure

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Ms. Joan E. Carletta, studying Microcircuit Testability at Cornell University.

Give a brief statement of laboratory and/or Dr. Warren Debany's (fellow's mentor) involvement with Ms. Joan E. Carletta.

Ms. Carletta was a Jr. Fellowship student in Dr. Debany's Group (Microcircuit Simulation and Testability Group) from Spring 1984 until Spring 1988. During the summer of 1988 (following her graduation from SUNY Buffalo) she worked in Dr. Debany's Group as a full-time employee. Her duties during this time consisted primarily of developing, enhancing, and maintaining a set of software tools that operate on a digital netlist language. These tools are the core of RADC's Testability Workbench project. Ms. Carletta developed translators that currently allow RADC access to twelve different logic simulators. She also developed tools that perform test generation, fault isolation, and computer network reliability evaluation.

Fred Diamond

Chief Scientist Date

8 May 1989

Mentor Date

S-789-000-032

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Joan E. Carletta | Semester: Fall 1988

University: Cornell University | Subcontract: S-789-000-032

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Electrical Engineering 541, Computer Processor Organization and Memory Hierarchy, Grade of A.

Electrical Engineering 544, VLSI Architectures and Algorithms, Grade of I.

Electrical Engineering 545, Computer Networks and Telecommunications I, Grade of A.

Mathematics 431, Introduction to Algebra I, Grade of A.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

With the guidance of my advisor, Dr. Franklin T. Luk, I read books and technical papers about fault-tolerant computing and related areas of interest. I learned to use the SUN work-station and several software packages, such as Matlab, that are necessary for my research. I attended lectures and seminars by guest speakers, and weekly meetings at which graduate students and faculty members with research interests similar to mine presented and discussed their results.

"I certify that all information stated is correct and complete."

Joan E. Carletta

Signature/Fellowship Recipient

Joan E. Carletta

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5019C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Joan E. Carletta is making satisfactory academic progress toward a Ph.D. in the area of Microcircuit Testability in the discipline of Electrical Engineering for the Fall 1988 semester."

Franklin Luk

Signature/Advising Professor

Dr. Franklin T. Luk

TYPED NAME/TITLE OF ADVISING PROFESSOR

5019C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Joel Alan DeKock Semester: Summer 1989

University: University of Wisconsin-Madison Subcontract: S-789-000-033

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Credits	Course	Grade
3	Intro-Statistical Methods	A
2	Research and Thesis	Progress

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Performed calculations to determine phase stabilities in the ternary systems Ti-Al-B and Ti-Al-O. Prepared powdered metal samples of TiAl-TiB_2, TiAl-Al_2O_3 and TiAl-SiC for heat treatment and evaluation of phase stability. All work done thus far has been preliminary and thus no progress yet on dissertation.

3. Give brief statement of your involvement with the Materials Laboratory Laboratory and Mr. Ted Nichols.

Received materials to work at Wright-Patterson for the summer, but chose not to.
Did not have any involvement with Mr Ted Nichols during the summer term.

"I certify that all information stated is correct and complete."

[signature]

Signature/Fellowship Recipient

Joel A. DeKock

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Joel Alan DeKock is making satisfactory academic progress toward a Ph.D. in the area of Intermetallic Compounds in the discipline of Materials for the Summer 1989 semester."

Signature/Advising Professor

Y. A. Chang

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Materials Laboratory requests the continuation of the AFOSR fellowship for Mr. Joel A. DeKock, studying Intermetallic Compound at University of Wisconsin-Madison.

Give a brief statement of laboratory and/or Dr. Ted Nicholas's (fellow's mentor) involvement with Mr. Joel A. DeKock.

Minimal involvement with mentor beyond discussions of areas of laboratory interest during first year which involved coursework primarily. Involvement in technical aspects of thesis is expected to increase in coming year

[signature] 29 Jun 89
Chief Scientist Date

[signature] 28 June 89
Mentor Date

S-789-000-033

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Joel A. DeKock   Semester: Spring 1989

University: University of Wisconsin-Madison   Subcontract: S-789-000-033

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Courses	Credits	Grade
1) Deformation of Solids - Elastic and plastic deformation, dislocation theory, fracture, fatigue, brittle failure and methods for mechanical properties measurement.	3	A
2) Theory of Alloy Phases - Electronic and thermodynamic principles governing the formation of alloy phases	3	AB
3) Advanced Materials Science: Diffusion and Reactions - Thermodynamics of multicomponent systems, reactions, diffusion and kinetics.	3	AB
4) Seminar - Materials science seminar	1	Satisfac

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

~~Perform~~

Preliminary investigation into Ti-Al-B ternary system - interest in reactions between the compounds TiAl and TiB_2. Have not identified dissertation topic. Dissertat. will be in the area of interface stability for high temperat composite materials.

"I certify that all information stated is correct and complete."

Joel DeKock

Signature/Fellowship Recipient

Joel A. DeKock

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5126C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Joel A. DeKock is making satisfactory academic progress toward a Ph.D. in the area of Intermetallic Compounds in the discipline of Metallurgy for the Spring 1989 semester."

6/5/89

Signature/Advising Professor

Y. AUSTIN CHANG
PROF & Chairman

TYPED NAME/TITLE OF ADVISING PROFESSOR

5126C

CONCURRENCE FORM

The Materials Laboratory requests the continuation of the AFOSR fellowship for Mr. Joel A. DeKock, studying Intermetallic Compound at University of Wisconsin-Madison.

Give a brief statement of laboratory and/or Dr. Ted Nicholas's (fellow's mentor) involvement with Mr. Joel A. DeKock.

Dr Nicholas spoke with student on phone at beginning of academic year and explained AF interests and some details of program. There was no further contact.

In telephone conversation w/ Ted Nicholas - He anticipates more interaction w/ Joel as he finishes his course work and begins his thesis - Sue Kirchoff

Chief Scientist Date

3 May 89

Mentor Date

S-789-000-033

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Joel Alan DeKock Semester: Fall 1988

University: University of Wisconsin-Madison Subcontract: S-789-000-033

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Principles of Corrosion (3 cr.) - Grade A. Thermodynamics / kinetics of metallic

Crystallography & X-Ray Diffraction (3 cr.) - Grade AB. crystal symmetry, projection ... X-ray studies of structural probl. solid state

Thermodynamics of Solids (3 cr.) Grade AB. thermodynamics of solids.

Seminar (1 cr) - Grade "Satisfactory". Topics in materials scien.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

No work towards disseration was performed during this semester. Group meetings were attended to aid identifying my thesis advisor, and what "New" work I could accomplis here at UW-Madison, in the area of Intermetallic Compounds.

At the beginning of the spring semester I changed advisors to Y.A. Chan and have tentatively decided to work on $TiAl + TiB_2$ (or SiC) composite

3. Give brief statement of your involvement with the Materials Laboratory Laboratory and Mr. Ted Nichols.

During the fall semester I had no direct involvement with the Materials Laboratory or Mr. Ted Nichols.

"I certify that all information stated is correct and complete."

[signature] (4/10/89)

Signature/Fellowship Recipient

Joel A. DeKock

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Joel Alan DeKock is making satisfactory academic progress toward a Ph.D. in the area of Intermetallic Compounds in the discipline of Materials for the Fall 1988 semester."

Signature/Advising Professor

Eric E. Hellstrom

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Christopher D'Souza Semester: Spring 1989

University: University of Texas/Austin Subcontract: S-789-000-034

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

I took two courses during the Spring of 1989.
1) Mission Analysis and Design - course grade A
2) Advanced Dynamics - course grade - Credit
(I took this course pass/fail)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the Spring Semester, I wrote the optimization code for a parametrized control for a short range missile (less than 5 miles of range). The technique which was used to accomplish this task was verified and the resulting trajectories correlated well with existing trajectory data

3. Give brief statement of your involvement with the Armament Laboratory Laboratory and Dr. Cloutier.

Late in the semester I received data for the missile model I am now doing research on (EMRAAT). Discussions with Dr. Cloutier and Johnny Evers confirmed that the direction which was being taken was valid

"I certify that all information stated is correct and complete."

Christopher N. D'Souza
Signature/Fellowship Recipient

Christopher N. D'Souza
TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Christopher D'Souza is making satisfactory academic progress toward a Ph.D. in the area of Optimal Guidance and Control in the discipline of Aerospace Engineering for the Spring 1989 semester."

David G. Hull

Signature/Advising Professor

David G. Hull Professor

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Armament Laboratory requests the continuation of the AFOSR fellowship for Mr. Christopher D'Souza, studying Optimal Guidance and Control at The University of Texas at Austin.

Give a brief statement of laboratory and/or Dr. James R. Cloutier (fellow's mentor) involvement with Mr. Christopher D. D'Souza.

Mr D'Souza has been developing new theory for the suboptimal implementation of an optimal midcourse guidance law. He has been able to develop a closed form solution to the problem by neglecting the aerodynamics. He is reintroducir the aerodynamics in a first order expansion and is making excellent progress in developing a closed form first order solution. It is expected that this first order solution will be very close to the optimal, nonimplementable solution. Mr D'Souza has been a real asset to our group and we're looking forward to having him here this coming summer.

James R Cloutier

12/1/89

Chief Scientist	Date	Mentor	Date

S-789-000-034

APR 21 1989

CONCURRENCE FORM

The Armament Laboratory requests the continuation of the AFOSR fellowship for Mr. Christopher N. D'Souza, studying Optimal Guidance and Control at The University of Texas at Austin.

Give a brief statement of laboratory and/or Dr. James R. Cloutier's (fellow's mentor) involvement with Mr. Christopher N. D'Souza.

Dr Cloutier is chief of the lab's optimal guidance research section and also directs D'Souza's work. Chris D'Souza will be spending the summer working at the lab.

[illegible signature] 4/13/89 — Chief Scientist, Date

[illegible signature] 12 Apr 89 — Mentor, Date

S-789-000-034

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Christopher D'Souza   Semester: Fall 1988

University: University of Texas/Austin   Subcontract: S-789-000-034

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   1. Stochastic Processes in Control, 3hrs, grade: A
      - uses of EKF and MGEKF in guidance
   2. Advanced Estimation Theory, 3hrs, grade: A
      - estimation in the presence of unmodeled accelerations
   3. Thesis - 6 hours - credit

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Developed and coded a parameterized optimization algorithm for midcourse guidance trajectories with maximum final energy. Wrote code which processed aerodynamic data into usable information

3. Give brief statement of your involvement with the Armament Laboratory Laboratory and Dr. Cloutier.

   The problem of maximum final energy trajectories is of interest to the Armament Laboratory and is in the area of Dr. Cloutier's expertise. I will be spending the summer at the Armament Laboratory refining and continuing research in this area.

"I certify that all information stated is correct and complete."

Christopher N. D'Souza
Signature/Fellowship Recipient

Christopher N. D'Souza
TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Christopher D'Souza is making satisfactory academic progress toward a Ph.D. in the area of Optimal Guidance and Control in the discipline of Aerospace Engineering for the Fall 1988 semester."

David G. Hull

Signature/Advising Professor

Dr. David G. Hull

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Aero Propulsion Laboratory requests the continuation of the AFOSR fellowship for Mr. David B. Ellsworth, studying Combustion Fluid Dynamics at Northwestern University.

Give a brief statement of laboratory and/or Dr. C. ~~A.~~ D. MacArthur's (fellow's mentor) involvement with Mr. David B. Ellsworth.

The only Laboratory involvement with Mr Ellsworth since his selection for the Laboratory Graduate Fellowship Program in 1988 was a brief telephone conversation with his mentor Dr C. D. MacArthur. Based on a review of Mr Ellsworth's research project, it is recommended that Dr Melvyn W. Roquemore be appointed as his mentor. Dr Roquemore's address and telephone number are:

WRDC/POSF
WPAFB OH 45433-6563
Tel - 513-255-6813

Edward J Curran 11 Apr 89

Chief Scientist Date

Charles D MacArthur 11 April 89

Mentor Date

S-789-000-035

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David B. Ellsworth

University: Northwestern University Subcontract: S-789-000-035

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   I registered for and passed three credits of 760-E90 (research) under the supervision of Professors Bayliss and Matkowsky.

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Attached.

"I certify that all information stated is correct and complete."

David B. Ellsworth
Signature/Fellowship Recipient

David B. Ellsworth
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David B. Ellsworth is making satisfactory academic progress toward a Ph.D. in the area of Combustion Fluid Dynamics in the discipline of Applied Mathematics for the Summer 1988 quarter."

B J Matkowsky
Signature/Advising Professor

Prof. Bernard J. Matkowsky
TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4669C

My current research project is to study downward flame propgation in a vertical cylindrical channel by analyzing both analytically and numerically the nonlinear problem that describes the motion of the flame front. In particular I am studying the evolution of a planar front into a steady, cellular front. During the summer of 1988, I developed a two-dimensional numerical code to model the nonlinear problem. The numerical code uses pseudo-spectral methods, and has been proved to be both efficient and accurate in describing the bifurcations from the steady, planar front.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David B. Ellsworth

University: Northwestern University　　　Subcontract: S-789-000-035

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   I registered for and passed three credits of 760-E90 (research) under the supervision of Profeessors Bayliss and Matkowsky. In addition I audited:

   760-D30-1 Wave Propagation
   760-E11 Nonlinear Buckling

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Attached.

"I certify that all information stated is correct and complete."

David B. Ellsworth
Signature/Fellowship Recipient

David B. Ellsworth
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David B. Ellsworth is making satisfactory academic progress toward a Ph.D. in the area of Combustion Fluid Dynamics in the discipline of Applied Mathematics for the Fall 1988 quarter."

Signature/Advising Professor

Prof. Bernard J. Matkowsky
TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4669C

During the fall of 1988, I used the two-dimensional numerical code to describe bifurcations from steady, planar fronts to steady, cellular fronts for certain channel radii. In addition, I completed a nonlinear analysis of the evolution problem by employing techniques of bifurcation theory. The major result of the analysis was the discovery that the steady, cellular front loses stability to a time pulsating front for certain channel radii. A comparison of the cellular solutions found by the numerical code and those predicted by the nonlinear analysis shows that the results are highly consistent.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David B. Ellsworth

University: Northwestern University Subcontract: S-789-000-035

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   I registered for and passed three credits of 760-E90 (research) under the supervision of Professors Bayliss and Matkowsky. In addition I audited:

   760-D30-2 Wave Propagation
   760-D26 Theory of Flows with Small Inertia

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Attached.

"I certify that all information stated is correct and complete."

David B. Ellsworth

Signature/Fellowship Recipient

David B. Ellsworth

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David B. Ellsworth is making satisfactory academic progress toward a Ph.D. in the area of Combustion Fluid Dynamics in the discipline of Applied Mathematics for the Winter 1989 quarter."

Matkowsky

Signature/Advising Professor

Prof. Bernard J. Matkowsky

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4669C

During the winter of 1989, I modified the two-dimensional numerical code to be more accurate in time, and looked for the analytically predicted time pulsating solutions. An example of a time-periodic solution was found. In addition, I began to prepare a manuscript based on the nonlinear analysis, for submission for publication.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David B. Ellsworth

University: Northwestern University   Subcontract: S-789-000-035

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   I registered for E98 (resident doctoral study). In addition I will audit:

   760-D30-3 Wave Propagation
   760-D27 Theory of Flows with Small Viscosity

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Attached.

"I certify that all information stated is correct and complete."

David B. Ellsworth

Signature/Fellowship Recipient

David B. Ellsworth

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David B. Ellsworth is making satisfactory academic progress toward a Ph.D. in the area of Combustion Fluid Dynamics in the discipline of Applied Mathematics for the Spring 1989 quarter."

Prof. Bernard J. Matkowsky

Signature/Advising Professor

Matkowsky

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4669C

During the spring of 1989, I plan to more fully describe the time pulsating solutions I found with the numerical code. I also plan to complete the manuscript based on the nonlinear analysis, and submit it for publication.

CONCURRENCE FORM

The H.G. Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Mr. James Frantz, studying Industrial and Systems Engineering/Humas Factors Engineering at University of Michigan.

Give a brief statement of laboratory and/or Mr. Joe McDaniel (fellow's mentor) involvement with Mr. James Frantz.

Involvement with mentor has been minimal. Mr. Frantz has declined opportunities to work in Air Force Labs.

George Mohr [signature] | Joe W. McDaniel [signature]

Chief Scientist Date 30 OCT 89

Mentor Date 19 Oct 89

S-789-000-036

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. James P. Frantz
University: The University of Michigan

Semester: Summer 1989
Subcontract: S-789-000-036

Fellow to complete

1. Courses - Give description of courses and grades received.

Title: Psychology 583 - Introduction to Survey Research (4 hrs.)

Description: The course addressed aspects all aspects of survey research. Topics covered in the course included: planning surveys, question design, questionnaire development, research designs, measurement and validity considerations in survey research, interviewing techniques and training, survey sampling techniques, modes of collecting data, coding data, data management, data analysis, and presentation. In addition to class lectures and reading, the class conducted an telephone survey, from beginning to end, for the Ann Arbor police department.

Grade: A+

Title: Industrial & Operations Engineering 590 - Directed Study Research and Special Problems II (2 hrs.)

Description: In this course I examined the factors that impact a person perception of a product or machine and proceeded to propose some methods of predicting the types of accidents that might occur with a given product. The goal of such predictive techniques is to evaluate, a priori, the effectiveness of safety related product literature (e.g., warnings, instructions, and labels) as well as product design features. During the term I evaluated accidents involving medical devices, industrial chemicals, all terrain vehicles, and other household products. I also researched the current state of knowledge regarding the factors that influence one's perception of risk and the effectiveness of safety related information.

Grade: Satisfactory (based on satisfactory/unsatisfactory)

2. Give a description of research and progress toward dissertation.

As mentioned in the previous progress report, the first three weeks of the term was spent preparing for and taking a series of qualifying examinations which I passed with superior ratings in all areas. Also this summer, I designed and conducted a survey aimed at assessing the effectiveness of certain features of a consumer product label. The survey involved interviewing 100 Canadian residents regarding their perceptions about a flammable adhesive product after they were exposed to various pieces of warning related information. The forthcoming data analysis and results should be of interest to the Canadian government, the U.S. Consumer Product Safety Commission and the manufacturers of building/construction/remodeling type products such as adhesives. This field experiment has provided me with valuable experience and a wealth of ideas for future research. I plan to present at least some of the results of this research at my "proseminar" which is another requirement of the PhD at Michigan.

"I certify that all information stated is correct and complete."

James Paul Frantz
Signature/Fellowship Recipient

James Paul Frantz
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5020C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. James P. Frantz is making satisfactory academic progress toward a Ph.D. in the area of Industrial and Systems Engineering/Human Factors Engineering in the discipline of Industrial and Systems Engineering for the Spring-Summer 1989 quarter."

James M. Miller
Signature/Advising Professor

JAMES M. MILLER ASSOCIATE PROFESSOR, INDUSTRIAL & OPERATIONS ENGINEERING
TYPED NAME/TITLE OF ADVISING PROFESSOR

5020C

CONCURRENCE FORM

The Armstrong Aerospace Medical Research Laboratory requests the continuation of the AFOSR fellowship for Mr.James P. Frantz, studying Industrial and Systems Engineering/Human Factors Engineering at The University of Michigan.

Give a brief statement of laboratory and/or Dr. Joe McDaniel's (fellow's mentor) involvement with Mr. James P. Frantz.

Involvement has been minimal. Mr. Frantz has declined the opportunity to do summer work at AAMRL or other Air Force lab.

George Mohr 16 JUL 89

Chief Scientist Date

Joe W McDaniel

Mentor Date

3 JULY 89

JOE MCDANIEL
AAMRL/HEG
WPAFB OH 45433-6573

S-789-000-036

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. James P. Frantz
University: The University of Michigan

Semester: Winter 1989
Subcontract: S-789-000-036

Fellow to complete

1. Courses - Give description of courses and grades received.

Title: Industrial & Operations Engineering (IOE) 539 - Safety Considerations in the Design of Industrial Machines and Processes (3 hrs.)

Description: Design/modification of machinery/products to eliminate or control hazards arising out of machanical, electrical, thermal, chemical, and motion energy sources. Application of retrospective and prospective hazard analysis, system safety, and accident reconstruction methodologies. Case examples: industrial machinery and trucks, construction and agriculture equipment, automated equipment, automated manufacturing systems/processes.

Grade: A

Title: IOE 466 - Statistical Quality Control (3 hrs.)

Description: Design and analysis of procedures for forecasting and control of production processes. Topics include attribute and variable sampling plans; sequential sampling plans; rectifying control procedures; charting, smoothing, forecasting and prediction of discrete time series.

Grade: A+

Title: IOE 563 - Labor and Legal Issues in Industrial Engineering (3 hrs.)

Description: A case study approach to engineering related issues in union-management relations, professional and product liability, and worker rights legislation. Analyses of accidents directed toward determining the facets of man-machine interaction which result in accidents and injuries.

Grade: A+

Title: IOE 522 - Theories of Administration (3 Hr.)

Description: Provides insights into leading theories concerning administration of research and industrial organizations. Treats the concepts needed for describing, assessing, and diagnosing organizations; process of organizational communication, motivation, and conflicts management; adaptation of organization systems to the requirements of work and information technologies.

Grade: A

Title: IOE 801 - Directed Research (1 hr.)

Description: Directed research on a topic of mutual interest to the student and the instructor. This course complements IOE 800, First Year Doctoral Seminar. My topic was product literature (instructions, labels, warnings, etc.) and their ability to enhance product use and safety. I annotated and editted the annotations of about 90 journal articles, reports, books, etc. which investigated various aspects of product literature.

Grade: Satisfactory (based on satisfactory/unsatisfactory)

2. Give a description of research and progress toward dissertation.

The first year of the PhD program at Michigan is primarily comprised of coursework which is designed to prepare a student for the qualifying exam. Thus, the courses listed above indicate progress toward fulfilling the requirements of the PhD. For three weeks immediately following the end of this semester I studied for and took the qualifying exam. I passed the exam with superior ratings in all of the exam areas. Passing the qualifying exam is the first major hurdle in obtaining a PhD at Michigan.

Other progress this term included annotating and editing annotations of journal articles, books, technical reports, etc. addressing instruction manuals, labeling systems, and warnings. Much of this was done as part of my directed study and has served to help in beginning to formulate some general research areas that may ultimately be a dissertation topic. Having analyzed a number of accidents involving consumer products, machinery, industrial equipment, etc. and having reviewed over a hundred articles addressing product literature and/or information, it is of interest to me to develop some cognitive based models of human interaction with products and machinery which are directed toward determining the reasons that people do or do not use product information. Such models and/or hypotheses may be useful in determining the way in which information should be conveyed as well as the type of information that should be presented.

"I certify that all information stated is correct and complete."

James Paul Frantz 5/30/89

Signature/Fellowship Recipient

James Paul Frantz

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5020C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. James P. Frantz is making satisfactory academic progress toward a Ph.D. in the area of Industrial and Systems Engineering/Human Factors Engineering in the discipline of Industrial and Systems Engineering for the Winter 1989 ~~quarter~~ Semester."

James M. Miller
Signature/Advising Professor

JAMES M. MILLER, ASSOCIATE PROFESSOR, INDUSTRIAL & OPERATIONS ENGINEER.
TYPED NAME/TITLE OF ADVISING PROFESSOR

5020C

CONCURRENCE FORM

The Human Resource Laboratory requests the continuation of the AFOSR fellowship for Mr. Craig Knoblock, studying Knowledge Acquisition and Artificial intelligence Techniques at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Lt. Col. Hugh Burns (fellow's mentor) involvement with Mr. Craig Knoblock.

Laboratory involvement with Mr. Knoblock has been primarily by telephone. We are interested in Mr. Knoblock's work in abstraction-based planning, as we find this work relevant to the problem of automated instructional planning.

Dr. Wes Regian

[signature] 10/31/89
Chief Scientist Date

J. Wesley Regian 10-27-89
Mentor Date

S-789-000-037

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Craig A. Knoblock is making satisfactory academic progress toward a Ph.D. in the area of Human Resources in the discipline of Computer Science for the Summer 1989 semester."

J. G. Carbonell

Signature/Advising Professor

Jaime G. Carbonell

TYPED NAME/TITLE OF ADVISING PROFESSOR

5021C

CONCURRENCE FORM

The Human Research Labortory requests the continuation of the AFOSR fellowship for Mr. Craig A. Knoblock, studying Knowledge Acquisition and AI Techniques at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Lt. Col. Hugh Burns's (fellow's mentor) involvement with Mr. Craig A. Knoblock.

Mr Craig Knoblock of Carnegie-Mellon University visited AFHRL/IDI on 10 Feb 89 and gave a two-hour presentation on his work in learning abstracts for his hierarchical planning. He discussed issues involved in the design and development of tools and intelligent tutoring systems with lab personnel. His efforts compliment research topics in knowledge acquisition and machine learning. We encourage Mr Knoblock to spend 10 weeks in our laboratory to facilitate the transition of his technology to our ongoing research and development of intelligent systems.

George [signature] 15 JUN 89

Chief Scientist Date

[signature] 14 Jun

Mentor Date

S-789-000-037

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Craig A. Knoblock — Semester: Spring 1989

University: Carnegie-Mellon University — Subcontract: S-789-000-037

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

I have completed all of my coursework.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I continued my work on learning abstractions for hierarchical planning. Please see attached paper, which has been accepted for publication.

"I certify that all information stated is correct and complete."

Craig A. Knoblock
Signature/Fellowship Recipient

Craig A. Knoblock
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5021C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Craig A. Knoblock is making satisfactory academic progress toward a Ph.D. in the area of Human Resources in the discipline of Computer Science for the Spring 1989 semester."

J G Carbonell

Signature/Advising Professor

Jaime G. Carbonell / Associate Professor

TYPED NAME/TITLE OF ADVISING PROFESSOR

5021C

LEARNING HIERARCHIES OF ABSTRACTION SPACES*

Craig A. Knoblock†
School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213
cak@cs.cmu.edu

ABSTRACT

Hierarchical planning is an effective technique for reducing search in planning. Previous work on hierarchical planning has primarily focused on using abstraction spaces; the question of how the abstractions are formed remained largely unexplored. This paper describes ALPINE, a system for learning abstraction spaces for use in hierarchical planning. Starting from only an axiomatization of the operators and example problems this system can learn detailed abstraction spaces for a domain. This is done using a theory of what makes a good abstraction space for hierarchical planning and then learning abstractions with the desired properties. The learned abstractions provide a significant performance improvement in PRODIGY, a domain-independent problem solver. The paper shows that ALPINE can produce more detailed and effective abstractions using less knowledge than ABSTRIPS, a well-known system that partially automated the formation of abstraction spaces.

INTRODUCTION

Complex planning and problem-solving tasks can be solved more effectively by using an abstract space to isolate the harder parts of the problems. *Hierarchical planning* exploits this idea by solving a problem in an abstract space and then using the resulting plan to guide the planning of the problem in a more detailed space. The abstract plan creates a number of simpler subproblems in the more detailed space and thus reduces the search over solving the original problem in this space. An *abstraction space* is a planning space in which some details of a problem are ignored. Planning in an abstraction space produces an *abstract plan*, which must then be elaborated into a detailed plan. In previous hierarchical planners (e.g., GPS (Newell and Simon, 1972), NOAH (Sacerdoti, 1977), and MOLGEN (Stefik, 1981)), with the exception of ABSTRIPS (Sacerdoti, 1974), the user had to provide the appropriate abstraction spaces. This paper describes a system for learning abstraction spaces, ALPINE, that produces more useful abstraction spaces than those produced by ABSTRIPS, starting with less initial domain knowledge.

ABSTRIPS

ABSTRIPS (Sacerdoti, 1974) is one of the few systems that attempted to automate the formation of abstractions for hierarchical planning. However, the system only partially automated this process. The user provided the system with an initial abstraction hierarchy, which was used to automatically assign criticalities to the preconditions of ground-level operators. First, ABSTRIPS placed the *static literals*, literals whose truth value cannot be changed by an operator, in the highest abstraction space. Then it placed literals that cannot be achieved with a "short" plan in the next highest abstraction space. The system placed the remaining literals at lower levels corresponding to their place in the user-defined abstraction hierarchy. The essence of the approach is the short-plan heuristic which separated the details from the important information. The system essentially produced a three-level abstraction hierarchy, with the static literals at the top of the hierarchy, the "important" literals next, and the details at the bottom. Any further refinement of levels came from the user-defined abstraction hierarchy.

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*To appear in the *Proceedings of the Sixth International Workshop on Machine Learning*, 1989.

†The author is supported by a graduate fellowship from Universal Energy Systems, Inc. under subcontract number S-789-000-037. This research was sponsored in part by the Office of Naval Research under contract number N00014-84-K-0415, and in part by the Defense Advanced Research Projects Agency (DOD), ARPA Order No. 4976, Amendment 20, under contract number F33615-87-C-1499. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressed or implied, of the Office of Naval Research, the Defense Advanced Research Projects Agency or the US Government.

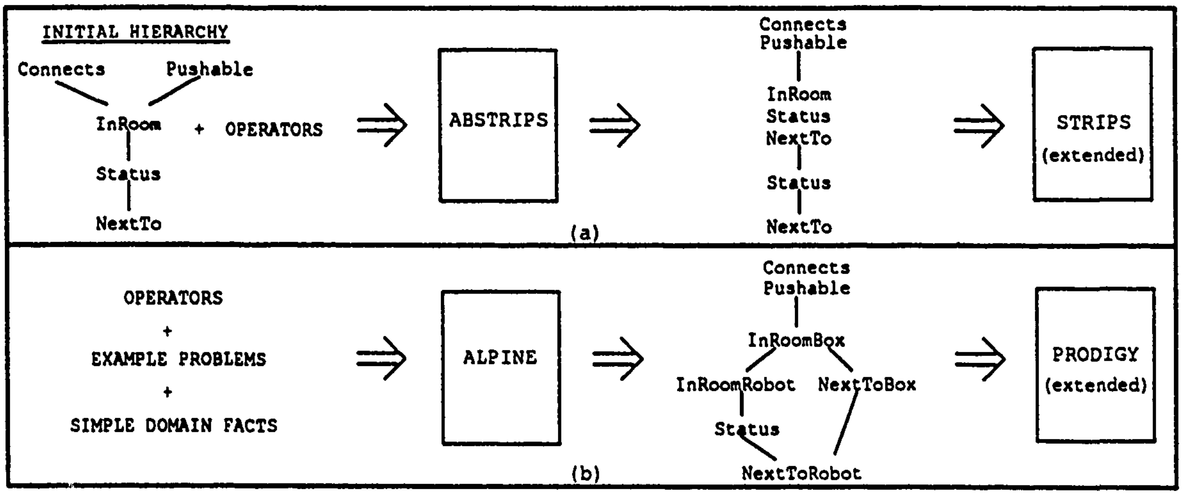

Figure 1: Comparison of ABSTRIPS and ALPINE

ABSTRIPS created abstractions for the STRIPS robot planning domain (Fikes *et al.*, 1972). The user provided as input to ABSTRIPS, the operator definitions and an initial abstraction hierarchy. Figure 1a shows both the abstraction hierarchy given and the abstraction hierarchy that ABSTRIPS produced for this domain. Some literals are placed at two different levels because the difficulty of achieving a particular precondition depends on the other preconditions of the operator in which it occurs. The only real difference between the given abstraction hierarchy and the final one is that some of the preconditions involving `Status` and `NextTo` were placed at the second level.

ALPINE

ALPINE is a domain-independent abstraction learner integrated with the PRODIGY planner (Minton, 1988). This section compares the representation, input, and output of ALPINE and ABSTRIPS, and shows that ALPINE produces better abstraction spaces than ABSTRIPS. The comparison is summarized in (Figure 1).

Abstraction spaces are represented in ALPINE by completely removing certain properties from the domain, forming reduced models as describe in (Tenenberg, 1988). Thus, sets of ground-level states are mapped into abstract states by completely removing classes of literals from both the operators and states. There are several advantages to this representation. First, there is a well-defined semantics for the abstraction spaces since they are formed by ignoring sets of constraints. Second, if operators and objects are indistinguishable at an abstract level, they can be combined into abstract operators or abstract object classes, which will reduce the branching factor of the search space. Third, the goal states are abstracted which simplifies the problem by providing constraints on the ordering of the goals and isolating the interactions among the goals. In contrast, ABSTRIPS represented abstraction spaces by assigning criticalities to preconditions, which does not have a well-defined semantics, permit the formation of abstract operators and objects, or allow the abstraction of the goal states.

The input to ALPINE is the operator definitions, a small set of problems, and some simple domain knowledge. The example problems are used to both guide the search for and to evaluate the utility of the abstraction spaces. The given domain knowledge is necessary to completely specify a domain. The additional domain knowledge provided for the robot planning domain is: (1) a domain-level axiom that states that if the robot is next to a door it will be in one of the rooms next to the door, (2) the types of the arguments of the predicates, which allows the system to distinguish between the same predicate with different arguments (e.g., `(in-room robot room)` is distinct from `(in-room box room)`). The information required to form abstractions by ALPINE is simply some example problems and knowledge about the domain, while ABSTRIPS required an initial abstraction hierarchy in order to form its final abstraction hierarchy.

Instead of producing a single abstraction hierarchy, ALPINE produces a partial order of abstraction spaces.

The advantage of a partial order is that the appropriate abstraction hierarchy depends on the problem to be solved, and the partial order allows the planner to select the abstraction hierarchy that is most appropriate for a given problem. (The techniques for selecting and using abstraction hierarchies are described in (Knoblock, 1988).) In addition, the abstraction hierarchies are not separated into conditions that can be achieved with either a "short" or "long" plan, but instead contain progressively easier levels in which to plan. The more fine-grained abstraction spaces allow the planner to isolate the harder parts of the problems to a greater extent and thus discover interactions faster. The partial order that ALPINE produces for the robot planning domain is shown in Figure 1b and represents three different possible abstraction hierarchies each of which contain six abstraction levels. In contrast, ABSTRIPS produced a single abstraction hierarchy that consisted of four levels.

ALPINE generates the partial order of abstraction spaces for the robot planning domain in 3.8 seconds of CPU time. The abstraction spaces that ALPINE produces are used in a version of the PRODIGY system extended to plan hierarchically. The table below shows the performance of PRODIGY without using abstraction, using the abstractions produced by ABSTRIPS, and using the abstractions produced by ALPINE on 200 randomly generated problems in the robot planning domain. PRODIGY was run in each configuration and given three minutes of CPU time to solve each of the problems. On average, ALPINE's abstraction spaces produced shorter solutions in less time than either of the other systems. The reason that ABSTRIPS performed so poorly is that in many of the harder problems. ABSTRIPS produced plans that violated the monotonicity property (described in the next section), which resulted in costly backtracking across abstraction levels.

	No Abstraction	ABSTRIPS	ALPINE
Average CPU Time (sec.)	47.1	81.3	25.2
Average Solution Length	32.6	30.3	28.5
Unsolved Problems	20	70	1

PROPERTIES OF ABSTRACT PLANS

This section defines two properties of abstract plans, *realizability* and *monotonicity*, which are used to form effective abstraction spaces. Realizability relates to whether or not an abstract plan can be refined into a detailed plan. Monotonicity relates to how the abstract plan is refined into a detailed plan.

An abstract plan is *realizable* if the conditions ignored at the abstract space are achievable in the ground space. A problem may be solvable in an abstract space, but there may not be a corresponding solution in the ground space. This is because an operator may be applicable in an abstract space, but the conditions ignored in the abstract space might not be achievable in the ground space. Finding abstraction spaces that are guaranteed to produce realizable abstract plans is difficult because it requires guaranteeing that there will always exist plans to achieve the conditions ignored in an abstract space. Whether a particular condition can be achieved will depend on the initial state, which can vary from problem to problem. However, an abstraction space may still be useful even if it does not always produce realizable abstract plans.

An abstract plan is *monotonic* if the structure of the abstract plan can be maintained while it is expanded into a solution in the ground space. The invariance of an abstract plan is important because the abstract plan is used to guide the search for a solution at the next level of detail. The structure of an abstract plan is defined as a set of tuples consisting of the conditions that hold in an abstract space and the interval over which they hold. Each tuple consists of a literal, the state in which the literal was achieved (possibly the initial state), and the state in which the literal is needed in order to apply an operator (possibly the goal state). The structure is maintained while an abstract plan is expanded and is thus monotonic if, for every tuple in the abstract plan, there is a corresponding tuple in every refinement of the plan.

ABSTRIPS would not necessarily form abstraction spaces that produced abstract plans that were either realizable or monotonic. In contrast, ALPINE learns abstraction spaces that are guaranteed to produce monotonic abstract plans. The resulting abstraction spaces are then tested empirically to remove abstractions whose benefit is outweighed by realizability problems. The remainder of the paper will focus on the monotonicity property and describe a particular technique for creating abstraction spaces that are guaranteed to produce monotonic abstract plans.

THE LEARNING METHOD

ALPINE takes the operators and some example problems and learns "good" abstraction spaces for a domain. Each operator consists of a conjunctive set of preconditions and effects. The system learns a partial order of abstraction spaces, which represents one or more abstraction hierarchies. ALPINE forms abstraction spaces by removing classes of literals, where each class of literals consists of one or more predicates and each predicate can be further subdivided based on the types of its arguments. The system guarantees the monotonicity property by proving that all of the literals in a class are achievable without interfering with the literals in a more abstract space. Thus, if there exists a refinement of an abstract plan, the plan can be refined while maintaining the structure of the abstract plan.

There are two possible ways that a plan to achieve a literal in some class could potentially delete literals in more abstract classes. First, if the plan contains an operator that adds or deletes a literal in a more abstract class as a side effect. This is a monotonicity violation caused by the effects of an operator. Second, if the plan contains an operator that has a precondition literal that is in a more abstract class and that precondition does not hold and so it will have to be achieved in order to complete the plan. This is a monotonicity violation caused by the preconditions of an operator. Thus, if the system can guarantee that a given class of literals can be achieved without causing either type of monotonicity violation, then the abstraction space formed by removing this class of literals will only produce monotonic abstract plans.

The system avoids monotonicity violations caused by the effects of operators by determining which literals an operator can clobber in the process of achieving a desired literal. There are two possible types of interactions. First, there are ***strong interactions***, where there are two literals such that there exists an operator that achieves each literal and clobbers the other one in the process. In this case, the classes of literals involved are combined into a single class since it would be pointless to place them at separate levels in an abstraction hierarchy. Second, there are ***weak interactions***, where an operator that achieves one literal clobbers another literal. In this case, the first class of literals should be placed either higher or at the same level in the abstraction hierarchy as the second class of literals. The complexity of this analysis is $O(n^2)$ in the number of operators because it requires comparing the effects of each operator to the effects of the other operators.

The system avoids monotonicity violations caused by the preconditions by proving that the operators used to achieve literals at one abstraction level will not subgoal on literals in a more abstract level. In the simplest case such an operator will not have any precondition literals that are in a more abstract space. In more complex cases, operators can have preconditions that always hold when the operator is used to achieve some condition in an abstract space. For example, the operator for opening a door requires that the robot is next to the door. However, the only time that the planner will need to open a door is when the robot is moving between rooms, and the operators for moving between rooms also test that the robot is next to the door. Within this context, the preconditions for opening a door will already be true.

ALPINE forms a partial order of abstraction spaces that is sufficient to guarantee that every plan produced by one of the abstraction spaces will be monotonic.[1] The system first creates an initial partial order by combining and ordering classes based on the strong and weak interactions. Then the initial partial order is further refined by showing that a particular class of literals can be dropped from the domain without risk of generating a subgoal higher in the abstraction hierarchy. In the case where a literal could cause an operator to subgoal on a literal that is in a more abstract space, the two corresponding classes of literals are combined. In the case where the condition can be guaranteed, the literals that must be higher in the hierarchy in order to make the guarantee are constrained to be above the other class by adding constraints to the partial order. The system starts at the bottom of the initial partial order and works upward combining classes and adding additional constraints as necessary until every abstraction space will only produce monotonic plans. Since the partial order is formed by adding constraints and combining groups of literals, it does not require searching through the $n!$ possible abstraction hierarchies. The complexity of constructing the partial order is $O(n^2)$ in the number of classes of literals.

[1] The final partial order only guarantees the monotonicity property for goals that consist of a single conjunct. For each problem, ALPINE then selects an abstraction hierarchy that is guaranteed to produce monotonic plans for the given goal, which may contain multiple conjuncts (Knoblock, 1988).

In general, finding abstraction spaces that guarantee precondition monotonicity can still be hard due to a large number of literal classes and inadequate domain knowledge. Both of these problems can be addressed by using example problem-solving traces to identify useful abstraction spaces. Simple heuristics can be used to identify classes of literals that are likely to make good abstractions. These heuristics include checking for literals that only occur on the leaves of the search tree or literals that can be removed without disturbing the structure of a plan. The use of examples addresses the search problem by providing classes of literals that are likely to form good abstraction spaces when they are removed. The problem of inadequate domain knowledge arises because the preconditions of operators may only indirectly state the conditions that must hold in order to apply the operator. For example, the operator for opening a door only requires that the robot is next to the door, it says nothing about what room the robot is in. However, the robot will always be in the room with the door if it is next to the door, but this information cannot be derived from the operators. The use of examples addresses the inadequate knowledge problem by providing a focus for the learner to either attempt to prove that a particular assertion holds or to initiate a focused dialogue with a domain expert to determine if the assertion is true. The current version of the system does not use examples. Instead, the system begins with sufficient knowledge about the domain to form the abstractions, and the domain is small enough to search the entire space.

CONCLUSIONS

This paper described a system that forms abstraction spaces for a planning domain from an axiomatization of a domain and a set of example problems. The paper identified the properties that constitute a useful abstraction space and then described a learner that used these properties to produce abstractions. The effectiveness of the learner is demonstrated by comparing the learned abstractions to those produced by ABSTRIPS as well as by showing that the abstractions improve performance in a planner. Work in progress includes extending ALPINE to run on more complex domains (e.g., an extended-STRIPS domain and a machine-shop scheduling domain (Minton, 1988)).

There has been a great deal of work on learning various types of control knowledge (e.g., macros, EBL, analogy, etc.). The type of plan knowledge learned by ALPINE is complementary to other types of learned knowledge. The system learns abstract domain theories which are not just an end in themselves, but can simplify and improve other types of learning. The use of an abstract domain theory in a learning system such as EBL, would simplify both the learning process as well as the learned knowledge.

Acknowledgments

I wish to thank Jaime Carbonell, Claire Bono, Oren Etzioni, Steve Minton, Tom Mitchell, Herb Simon, Josh Tenenberg, and Manuela Veloso for their many helpful comments on this work.

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CONCURRENCE FORM

The Human Research Labortory requests the continuation of the AFOSR fellowship for Mr. Craig A. Knoblock, studying Knowledge Acquisition and AI Techniques at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Lt. Col. Hugh Burns's (fellow's mentor) involvement with Mr. Craig A. Knoblock.

Mr. Knoblock is performing important work in the area of automated generation of abstractions for planning in large domains. While the Intelligent Systems Branch has monitored his progress by electronic mail and telephone, direct contact with Mr. Knoblock has been minimal. As Mr. Knoblock enters that part of his Ph.D. program which allows more time for individual effort, his direct interactions with the branch will increase. For example, Mr. Knoblock will be visiting the Human Resources Lab on 9 and 10 February to formally present the results of his research. At that time, Dr. Regian (IDI Senior Scientist) and Lt Col Burns (IDI) will discuss a summer internship at HRL with Mr. Knoblock.

9 Feb 89 | | 3-Feb-8
Chief Scientist Date | | Mentor Date

S-789-000-037

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Craig A. Knoblock

Semester: Fall 1988

University: Carnegie-Mellon University

Subcontract: S-789-000-037

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

I have already completed my course work and I am working on my thesis.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

I presented my thesis proposal in the fall semester. I have enclosed a copy of the proposal.

"I certify that all information stated is correct and complete."

Craig A. Knoblock

Signature/Fellowship Recipient

Craig A. Knoblock

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5021C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Craig A. Knoblock is making satisfactory academic progress toward a Ph.D. in the area of Human Resources in the discipline of Computer Science for the Fall 1988 semester."

Jaime G. Carbonell

Signature/Advising Professor

Professor Jaime G. Carbonell

TYPED NAME/TITLE OF ADVISING PROFESSOR

5021C

Carnegie Mellon

Department of Computer Science
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213-3890

15 Dec. ber 1988

Craig Knoblock
Computer Science Department
Carnegie Mellon University
Pittsburgh, PA 15213

Dear Craig:

In the semiannual evaluation of all our students the faculty reviewed your progress toward the Ph.D. We were happy to see the presentation of your thesis proposal this semester on automated generation of abstractions for planning in large domains in PRODIGY. We expect you to keep your sights and efforts focused on the thesis research, both analysis and implementation.

Keep up the good work!

Sincerely,

AN Habermann

A. N. Habermann
Professor and Department Head

srb
cc: J. Carbonell

A Theory of Abstraction for Hierarchical Planning*

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Abstract

Hierarchical planning is widely acknowledged as an effective technique for reducing search, but the properties that make the technique effective are not well understood. This paper formally defines hierarchical planning, shows that the technique can reduce an exponential search space to a linear one, and identifies the assumptions under which this analysis holds. Since these assumptions would be difficult to guarantee in general, the paper identifies the monotonicity property, a heuristic for evaluating abstraction spaces. Lastly, the paper presents an algorithm for producing abstractions with this property and then describes how the algorithm completely automates a reformulation of the Tower of Hanoi puzzle, which reduces the search space of the puzzle from exponential to linear.

*To appear in D. P. Benjamin (Ed.), *Change of Representation and Inductive Bias*. Boston, MA: Kluwer.

†The author is supported by an Air Force Laboratory Graduate Fellowship through the Human Resources Laboratory at Brooks AFB. This research was sponsored in part by the Office of Naval Research under contract number N00014-84-K-0415, and in part by the Defense Advanced Research Projects Agency (DOD), ARPA Order No. 4976, Amendment 20, under contract number F33615-87-C-1499. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressed or implied, of the Office of Naval Research, the Defense Advanced Research Projects Agency or the US Government.

INTRODUCTION

Hierarchical planning is a technique that solves problems by first mapping the problem into an abstract space, solving an abstract version of the problem, and then using the abstract solution to guide the search for a solution to the original problem. The idea is that the abstract solution can be used to form smaller subproblems, thus reducing the complexity of the overall problem.

Hierarchical planning was first used in Planning GPS [Newell and Simon, 1972], although the ideas were discussed prior to Planning GPS in both Minsky[1963] and Polya[1945]. The technique has since been used in a number of planning systems [Sacerdoti, 1974, Sacerdoti, 1977, Stefik, 1981, Tate, 1976, Vere, 1983, Wilkins, 1984]. The advantages of hierarchical planning are widely acknowledged. However, there has not been a careful analysis of the potential benefits or the conditions under which the technique is effective. In addition, finding "good" abstractions for hierarchical planning is largely a black art, where the implementors of each system hand-craft abstractions for each problem domain.

This paper provides a formal definition of hierarchical planning, gives an analysis of the potential performance improvement that the technique provides, and identifies the assumptions that underlie the technique and its analysis. The analysis shows that under a restrictive set of conditions, hierarchical planning can reduce an exponential search space to a linear one. The analysis extends Korf's result [Korf, 1987] from planning with a hierarchy of macros to hierarchical planning. In addition, this paper identifies and formally defines the monotonicity property, which is used as the basis of an algorithm for creating abstraction spaces for hierarchical planning. The paper describes the algorithm, proves the algorithm is correct, and shows that the complexity of the algorithm is quadratic. Lastly, the paper describes the abstraction spaces generated by the algorithm on the Tower of Hanoi puzzle and shows that these abstraction spaces produce an exponential reduction in the size of the search space.

HIERARCHICAL PLANNING

This section defines planning, builds on this definition to define two-level hierarchical planning, and extends the two-level definition to multiple levels.

Planning

This section adopts the notation of Lifschitz[1986] to define operators and plans. Given a first-order language L, S is the set of states, where a state is a finite and consistent set of atomic sentences of L. O is the set of operators, where each operator α has a corresponding triple (P_α, D_α, A_α). The precondition P_α is a sentence in L, and both the delete list D_α and add list A_α are finite sets of atomic sentences in L.

A planning problem consists of:

- An initial state $S_0 \in S$.
- A goal state $S_n \in S$.
- Set of operators, $Op \subset O$.

Let $\mathcal{P} : S \times S \times O \rightarrow O^*$ be a function that is given an initial state S_0, a final state S_n, and a set of operators Op, and produces a finite sequence of instantiated operators[1] $\bar{\alpha}$, called a *plan*, that transforms the initial state into the final state.

$$\bar{\alpha} = \mathcal{P}(S_0, S_n, Op)$$

The $\|$ symbol indicates concatenation of plans or operators. Each plan $\bar{\alpha} \equiv \alpha_1 \| \ldots \| \alpha_n$, defines a sequence of states $S_0, S_1, \ldots, S_n$, where the following conditions hold:

$$\begin{aligned} S_{i-1} &\vdash P_{\alpha_i} \, ; \; i = 1, \ldots n \\ S_i &= (S_{i-1} \setminus D_{\alpha_i}) \cup A_{\alpha_i} \, ; \; i = 1, \ldots n \end{aligned}$$

The first formula says that for each operator in the plan, the precondition of that operator must hold in the state in which the operator is applied. The second formula says that the state immediately following the application of an operator is equivalent to the union of the add list with the set difference of the previous state and the delete list.

Let $\mathcal{A} : O^* \times S \rightarrow S$ be a function that applies a plan to a state to produce a new state. The result of applying the plan $\bar{\alpha}$ to the initial state S_0, is the state S_n:

$$S_n = \mathcal{A}(\bar{\alpha}, S_0)$$

[1]The paper uses the same notation for an operator schema and an instantiated operator. However, it is usually clear from context which one the paper is referring to since a plan is composed of instantiated operators.

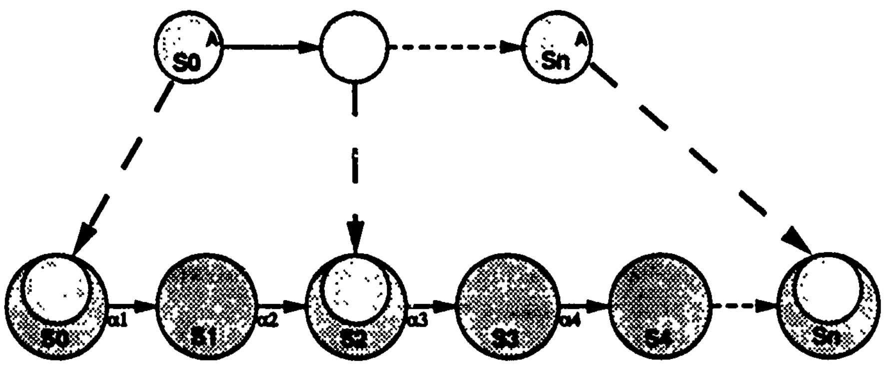

Figure 1: Two-level Hierarchical Planning.

Two-level Hierarchical Planning

Two-level hierarchical planning involves two planning spaces: the original planning space (called the *base space*) and the abstract planning space (called the *abstraction space*). An abstraction space is defined in terms of the operators O^A and states S^A in the language L^A.

A hierarchical planner is given the initial state $S_0 \in S$, the final state $S_n \in S$, the operators in the base space $Op \subset O$, and the operators in the abstraction space $Op^A \subset O^A$. In addition, a hierarchical planner requires a planning function $\mathcal{P} : S \times S \times O \rightarrow O^*$ that plans in the base space, an abstract planning function $\mathcal{P}^A : S^A \times S^A \times O^A \rightarrow O^{A^*}$ that plans in the abstract space, a mapping function $\mathcal{M} : S \rightarrow S^A$ that maps base states into abstract states, an abstract mapping function $\mathcal{M}^A : S^A \rightarrow S$ that maps abstract states into base states, an application function $\mathcal{A} : O^* \times S \rightarrow S$ that applies a plan to a state to produce a new state, and an abstract application function $\mathcal{A}^A : O^{A^*} \times S^A \rightarrow S^A$ that applies an abstract plan to an abstract state to produce a new abstract state. The output of a hierarchical planner is a sequence of operators in the base space that transforms the initial state into the final state.

A hierarchical planner solves a problem by first mapping a problem into an abstract space, solving the abstract problem, using the abstract solution to form subproblems in the base space, and solving each of the subproblems. This is shown pictorially in Figure 1. More formally this procedure is defined as follows: first, the initial and goal states S_0 and

S_n are mapped into abstract states S_0^A and S_n^A.

$$S_0^A = \mathcal{M}(S_0) \qquad S_n^A = \mathcal{M}(S_n) \tag{1}$$

Then the abstract planning function is used to find a sequence of operators from Op^A that transforms state S_0^A into state S_n^A. This produces an *abstract plan* $\bar{\alpha}^A \in O^{A^*}$.

$$\bar{\alpha}^A = \mathcal{P}^A(S_0^A, S_n^A, Op^A) \tag{2}$$

The solution to the abstract problem defines a set of intermediate abstract states. The intermediate states are found by decomposing the abstract plan $\bar{\alpha}^A$ into its component operators and applying each of these operators to successive states starting with the initial abstract state S_0^A.

$$\bar{\alpha}^A \equiv \alpha_1^A \| \ldots \| \alpha_n^A \tag{3}$$

$$S_i^A = \mathcal{A}^A(\alpha_i^A, S_{i-1}^A)\ ;\ i = 1, \ldots, n \tag{4}$$

The intermediate abstract states are mapped into base states and used as goals for the subproblems in the base space. (If the language of the abstract space is a subset of the base space, then $\mathcal{M}^A$ is simply the identity function and an abstract state will serve directly as a goal in the base space.) The subproblems can be solved sequentially by first solving for $\bar{\alpha}_1$, then using that result to find S_1, next solving for $\bar{\alpha}_2$, and so on up to S_{n-1}.

$$\bar{\alpha}_i = \mathcal{P}(S_{i-1}, \mathcal{M}^A(S_i^A), Op)\ ;\ i = 1, \ldots, n-1 \tag{5}$$

$$S_i = \mathcal{A}(\bar{\alpha}_i, S_{i-1})\ ;\ i = 1, \ldots, n-1 \tag{6}$$

The final subproblem contains S_n as the goal.[2]

$$\bar{\alpha}_n = \mathcal{P}(S_{n-1}, S_n, Op) \tag{7}$$

The solution to the original problem is simply the concatenation of the solutions to all of the subproblems.

$$\bar{\alpha} = \bar{\alpha}_1 \| \bar{\alpha}_2 \| \ldots \| \bar{\alpha}_n \tag{8}$$

[2]Note that as a refinement to this hierarchical planning method the planner could first achieve $\mathcal{M}^A(S_n^A)$ and then S_n, since $\mathcal{M}^A(S_n^A) \subseteq S_n$.

Multi-level Hierarchical Planning

Two-level hierarchical planning is easily extended to multiple levels. Instead of two operator sets, there is a hierarchy of operator sets. The relationship between any two levels that are adjacent in the hierarchy is exactly the same as the relationship between the abstract space and the original space in the two-level formulation.

ANALYSIS OF HIERARCHICAL PLANNING

This section presents a worst-case complexity analysis of single-level planning, two-level hierarchical planning, and multi-level hierarchical planning. The analysis is based on the analysis of abstraction planning with macros by Korf[1987]. Korf showed that the use of a hierarchy of macros can reduce an exponential search to a linear one. However, as Tenenberg[1988, p.74] points out, Korf's analysis makes a number of assumptions that do not hold for hierarchical planning. For example, Korf's analysis assumes that when the abstract problem is solved, the original problem is solved, while in hierarchical planning the abstract solution has to be mapped into a solution in the base space. The last part of this section identifies under precisely what assumptions hierarchical planning can reduce an exponential search to a linear one. The outline of this section is the same as the previous one – the analysis is done for planning, two-level hierarchical planning, and multi-level hierarchical planning. Since the size of the search spaces are potentially infinite, the analysis assumes the use of a brute-force search procedure that is bounded by the length of the solution (e.g., depth-first iterative-deepening). Following the analysis is a discussion of the additional assumptions made in the analysis.

Planning

For planning, if a problem has a solution of length l and the search space has a average branching factor b, then the size of the search space is $\sum_{i=1}^{l} b^i$. Thus, the worst-case complexity of this problem is $O(b^l)$.

Two-level Hierarchical Planning

Let k be the ratio of the solution length in the base space to the solution length in the abstract space. Thus, l/k is the solution length in the abstract space, and b is the branching factor in the abstract space. The size of the search tree in the abstract space is $\sum_{i=1}^{l/k} b^i$, which is $O(b^{l/k})$. However, the analysis must also include the use of this abstract solution to solve the original problem.

The abstract solution defines l/k subproblems, where the size of each problem $d(S_i^A, S_{i+1}^A)$ is the number of steps in the base space required to transform the abstract state S_i^A into the abstract state S_{i+1}^A.

$$b^{d(S_0^A, S_1^A)} + b^{d(S_1^A, S_2^A)} + \ldots + b^{d(S_{l/k-1}^A, S_{l/k}^A)}$$

which is $O(b^{d_{\max}})$, where

$$d_{\max} \equiv \max_{0 \leq i \leq l/k-1} d(S_i^A, S_{i+1}^A)$$

In the ideal case, the abstract solution will divide the problem into subproblems of equal size, and the length of the final solution using abstraction will equal the length of the solution without abstraction. In this case, the abstract solution divides the problem into l/k subproblems of length k.

$$b^{d_{\max}} = b^{l/(l/k)} = b^k$$

Assuming that the planner can first solve the abstract problem and then solve each of the problems in the base space without backtracking across problems, then the size of the space searched in the worst case is the sum of the search spaces for each of the problems.

$$\sum_{i=1}^{l/k} b^i + \frac{l}{k} \sum_{i=1}^{k} b^i$$

The complexity of this search is: $O(b^{l/k} + \frac{l}{k} b^k)$. The high-order term is minimized when $l/k = k$, which occurs when $k = \sqrt{l}$. Thus, when $k = \sqrt{l}$, the complexity is $O(\sqrt{l}\, b^{\sqrt{l}})$, compared to the original complexity of $O(b^l)$.

Multi-level Hierarchical Planning

Korf[1987] showed that a hierarchy of macro spaces can reduce the expected search time from $O(n)$ to $O(\log n)$, where n is the size of the search space. This paper proves an analogous result – that multi-level hierarchical planning can reduce the size of the search space for a problem of length l from $O(b^l)$ to $O(l)$.

In general, the size of the search space with n levels (where the ratio between the levels is k) is:

$$\sum_{i=1}^{\frac{l}{k^{n-1}}} b^i + \frac{l}{k^{n-1}} \sum_{i=1}^{k} b^i + \frac{l}{k^{n-2}} \sum_{i=1}^{k} b^i + \frac{l}{k^{n-3}} \sum_{i=1}^{k} b^i + \ldots + \frac{l}{k} \sum_{i=1}^{k} b^i$$

The first term in the formula accounts for the search in the most abstract space. Each successive term accounts for the search in successive abstraction spaces. Thus, after solving the first problem, there are l/k^{n-1} subproblems that will have to be solved at the next level. Each of these problem are of size k since that is the ratio of the solution lengths between levels. At the next level there are l/k^{n-2} subproblems $(k * l/k^{n-1})$ each of size k, and so on. In the final level there are l/k subproblems each of size k. The final solution will therefore be of length $l/k * k = l$.

The maximum reduction in search can be obtained by setting the number of levels n to $\log_c(l)$ and the ratio between levels k to the base of the logarithm c. Substituting these values for n and k in the formula above produces the following formula:

$$\sum_{i=1}^{c} b^i + c\sum_{i=1}^{c} b^i + c^2\sum_{i=1}^{c} b^i + c^3\sum_{i=1}^{c} b^i + \ldots + c^{\log_c(l)-1} \sum_{i=1}^{c} b^i$$

Since there are $\log_c(l)$ terms (one for each abstraction level), the exponents of all the terms are equal, and the coefficients of the terms are monotonically increasing, the largest term is the last one. Since $c^{\log_c(l)-1}$ is equal to l/c, the complexity of this search space is $O(\frac{l}{c}b^c)$. This is simply $O(l)$ since b and c are fixed. Thus, the complexity for $\log_c(l)$ levels of abstraction where the ratio between the solutions at each level is c is $O(l)$, compared to the original complexity of $O(b^l)$.

In practice, it will not always be possible to find $\log(l)$ abstraction levels with the optimal ratio between levels. In addition, there are several assumptions made in this analysis that will not always hold in practice. The violation of these assumptions will reduce the effectiveness of hierarchical planning. These assumptions are described below and the first two assumptions are illustrated graphically in Figure 2.

Assumptions

1. *There is no backtracking across abstraction levels.* Every solution at an abstract level can be refined into a solution at lower levels. This is shown in Figure 2 by the horizontal black line that indicates there is no backtracking across levels. In practice there may be more than one way to solve a problem in an abstract space, and the particular way in which it is solved may preclude solving the problem at lower levels. Thus, it might be necessary to backtrack across levels. This assumption corresponds to what Tenenberg calls the *downward solution property* [Tenenberg, 1988].

2. *There is no backtracking across subproblems within an abstraction level.* The solution to each of the subproblems will not prevent any of the remaining subproblems at the same level of abstraction from being solved. This is shown in Figure 2 by the vertical black line that indicates there is no backtracking across subproblems within a level. In practice, it might be necessary to backtrack across subproblems to find a consistent solution to all of the subproblems.

3. *The problem is decomposed into subproblems that are all of equal size.* The analysis assumes that the size of all the subproblems are the same in order to minimize $d_{\max}$. The subproblems are represented by ovals in Figure 2. If this assumption does not hold, a hierarchical planner can still achieve large reductions in search. In general, as long as the first two assumptions hold, the complexity of the search using hierarchical planning will be the complexity of the largest subproblem in the search. For example, if the largest subproblem is $b^{\frac{l}{2}}$, hierarchical planning would still reduce the search from $O(b^l)$ to $O(b^{\frac{l}{2}})$.

4. *The hierarchical planner produces the shortest solution.* If a problem has a solution of length l, then the length of the solution produced using abstraction will also be l. In practice, dividing up a problem into abstraction levels may prevent the planner from finding the shortest solution to a problem.[3]

[3] If a depth-first search procedure is used, then hierarchical planning may produce better solutions simply because the problem solver is not mislead by the details of the problem.

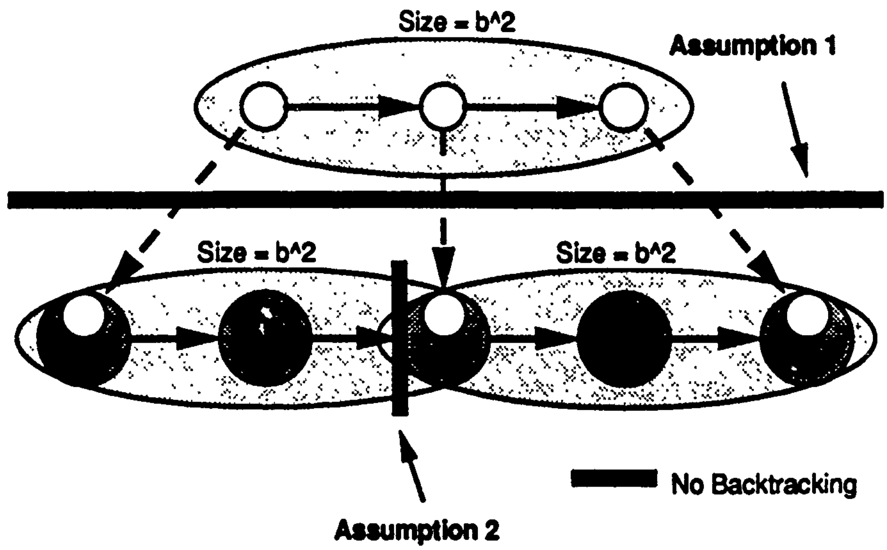

Figure 2: Assumptions of the Analysis.

Another assumption made in the analysis is that the average branching factor b is assumed to be constant across the levels of abstraction. In fact, the average branching factor may actually be reduced (never increased since operators can only be removed) at higher levels of abstraction, thereby providing an additional reduction in the search space.

This analysis identifies a sufficient set of assumptions under which hierarchical planning can provide a dramatic reduction in the search space.[4] Unfortunately, these assumptions will not hold in all domains, and if they do hold, it may not be possible to determine that fact *a priori*. For example, determining whether an abstract solution can be refined requires determining whether plans exist to solve the subproblems, which is undecidable [Chapman, 1987]. The next section describes the monotonicity property, which is a heuristic for evaluating the utility of an abstraction, and the section after that describes how this property can be used to generate abstractions for hierarchical planning.

[4]Actually, the third and fourth assumptions are stronger than necessary since a search space could be reduced from exponential to linear despite small variations in the maximum problem size and final solution length.

THE MONOTONICITY PROPERTY

The previous section identified a set of conditions for hierarchical planning that are sufficient to reduce the size of the search space from exponential to linear. Unfortunately, it would be impossible, except in a few rare cases, to guarantee that an abstraction met the conditions described in the previous section. In general, the usefulness of an abstraction space depends on the degree to which these conditions hold, not on whether or not these conditions hold.

Probably the most important assumptions (and the least likely to hold in practice) are the third assumption, which requires that a problem can be decomposed into equal size subproblems, and the fourth assumption, which requires that the final solution is the shortest one possible. If these conditions were removed, the remaining two conditions would guarantee that a solution in the abstract space can be refined into a solution in the base space, but those conditions would not specify much about the structure of the refinement. The refinement would have to pass through the intermediate states of the abstract plan, but there would be nothing to prevent a planner from violating the abstract solution to a problem and solving the same problem in different way. The result could be that the problem effectively gets re-solved at each level of abstraction. Tenenberg[1988, p.75] points out that if the operators in a domain are invertible, then there is no clear criterion for failure in specializing a plan, and a planner could specialize a plan *ad infinitum* simply by inserting increasing length solutions between the steps of the abstract plan. In other words, without the third and fourth assumptions, even though an abstract problem can be specialized into a detailed solution, it may not be a useful outline for solving the problem.

Consider the way in which people appear to use abstractions – they find an abstract solution to a problem that addresses the hardest part of the problem and then fill in the details. Since the abstract solution solves the hard part of the problem, the final solution will contain the structure of the abstract solution. This leads to the definition of the monotonicity property, which requires that a refinement of an abstract plan maintains the structure of that plan. The remainder of this section precisely defines the monotonicity property. Although the property is neither necessary nor sufficient for a good abstraction space, it is a surprisingly good heuristic for producing useful abstractions.

A Formal Definition of Monotonicity

The monotonicity property captures the idea that as an abstract solution is refined, the structure of the abstract solution is maintained. Before stating the formal definition of monotonicity, this section first defines both the structure and refinement of an abstract plan. First, consider the definitions of the *producer*, *user*, and *enablement* properties, which are used to capture the structure of a plan, based on similar properties defined by Anderson[1988].

Let $\mathcal{G} : L \times S \times O^*$ be a relation that defines a literal l (a possibly negated atomic formula) that is *produced* at state s, in a plan $\bar{\alpha}$, where $\bar{\alpha} \equiv \alpha_1 \| \ldots \| \alpha_i \| \ldots \| \alpha_n$.

$$\begin{aligned} \mathcal{G}(l, s, \bar{\alpha}) \;\equiv\; & [(s = S_i) \wedge (l \in A_{\alpha_i} \cup D_{\alpha_i})] \\ & \vee [(s = S_0) \wedge (l \in S_0)] \end{aligned}$$

This says that a literal is produced at some state in a plan if one of two conditions hold: either the literal occurs in the effects of some operator in the plan or the literal occurs in the initial state.

Let $\mathcal{U} : L \times S \times O^*$ be a relation that defines a literal l that is *used* at state s, in a plan $\bar{\alpha}$, where $\bar{\alpha} \equiv \alpha_1 \| \ldots \| \alpha_i \| \ldots \| \alpha_n$.

$$\begin{aligned} \mathcal{U}(l, s, \bar{\alpha}) \;\equiv\; & [(s = S_{i-1}) \wedge (l \in P_{\alpha_i})] \\ & \vee [(s = S_n) \wedge (l \in S_n)] \end{aligned}$$

This says that a literal is used at some state in a plan if one of two conditions hold: either the literal occurs as a precondition of some operator in the plan or the literal occurs in the goal state.

The function $\mathcal{E} : O^* \rightarrow 2^{(L \times S \times S)}$ defines the set of *enablements* of a plan $\bar{\alpha}$, where each *enablement* consists of a literal l that holds in a plan from the state S_j in which l is produced to the state S_k in which l is used.

$$\begin{aligned} \mathcal{E}(\bar{\alpha}) = \{(l, S_j, S_k) \; : \quad & \mathcal{G}(l, S_j, \bar{\alpha}) \wedge \\ & \mathcal{U}(l, S_k, \bar{\alpha}) \wedge \\ & (l \in S_j) \wedge (l \in S_{j+1}) \wedge \ldots \wedge (l \in S_k)\} \end{aligned}$$

This says that the set of enablements for an abstract plan consists of the literals in the plan that are each produced at some state S_j and hold until they are used at some state S_k. Note that a literal can be produced and used in the same state.

Next, consider the definitions of a *refinement* of an abstract plan and a *specialization* of an abstract state. Let $\mathcal{R} : O^{A^*} \times O^*$ be a relation such that $\mathcal{R}(\bar{\alpha}^A, \bar{\alpha})$ says that $\bar{\alpha}$ is a *refinement* of $\bar{\alpha}^A$ and let $\mathcal{S} : S^A \times S$ be a relation such that $\mathcal{S}(S_i^A, S_i)$ says that S_i is a *specialization* of S_i^A. $\mathcal{R}(\bar{\alpha}^A, \bar{\alpha})$ and $\mathcal{S}(S_i^A, S_i)$ hold if the relationships between $\bar{\alpha}^A, \bar{\alpha}$ and S_i^A, S_i hold in formulas 3 through 8 in the previous section. In other words, $\bar{\alpha}$ is a refinement of $\bar{\alpha}^A$ if $\bar{\alpha}$ can be derived from $\bar{\alpha}^A$, and S_i is a specialization of S_i^A if S_i is generated from S_i^A in the hierarchical planning procedure.

These definitions of the structure and refinement of an abstract plan are used to define the monotonicity property. Let $\mathcal{R}_m : O^{A^*} \times O^*$ be a relation such that $\mathcal{R}_m : (\bar{\alpha}^A, \bar{\alpha})$ states that $\bar{\alpha}$ is a *monotonic refinement* of $\bar{\alpha}^A$.

$$\begin{aligned}\mathcal{R}_m(\bar{\alpha}^A, \bar{\alpha}) \equiv\ & \mathcal{R}(\bar{\alpha}^A, \bar{\alpha}) \wedge \\ & \forall (l,p,u)\ \{(l,p,u) \in \mathcal{E}(\bar{\alpha}^A) \rightarrow \\ & \exists (l,p',u')[(l,p',u') \in \mathcal{E}(\bar{\alpha}) \ \wedge\ \mathcal{S}(p,p') \ \wedge\ \mathcal{S}(u,u')]\}\end{aligned}$$

This states that the plan $\bar{\alpha}$ is a monotonic refinement of the abstract plan $\bar{\alpha}^A$ if and only if $\bar{\alpha}$ is a legal refinement of the abstract plan and for every enablement in the abstract plan there is a corresponding enablement in $\bar{\alpha}$. The corresponding enablements are those that hold for the same literals[5] between states that are specializations of the abstract states.

The definition of a monotonic refinement is used to define a monotonic abstraction space.[6] An abstraction space is a *monotonic abstraction space* if the following condition holds: if there exists a solution to a problem, then there exists a solution in the abstraction space and that solution has a monotonic refinement. (Note that for a solution to be considered valid, every operator in the solution must either directly or indirectly achieve the goal. An operator indirectly achieves a goal by

[5]This assumes that the language of the abstract space is a subset of the language of the more detailed space. If this is not the case, then the enablement relation must hold for the *corresponding* literal or literals.

[6]One could also define a *monotonic abstract plan* such that $\bar{\alpha}^A$ is a monotonic abstract plan iff: $\exists x \mathcal{R}(\bar{\alpha}^A, x) \rightarrow \exists y \mathcal{R}_m(\bar{\alpha}^A, y)$].

achieving a precondition of another operator that directly or indirectly achieves the goal.) The definition of a monotonic abstraction space is easily extended to a *hierarchy of monotonic abstraction spaces* as follows: if there exists a solution to a problem, then there exists a solution to that problem in the highest (most abstract) abstraction space and that solution can be monotonically refined into each successive level in the hierarchy.

The monotonicity property avoids the unbounded refinement of abstract plans by requiring that a refined plan maintain the structure of an abstract plan. Since the property prevents a system from undoing the work performed at a higher level, it prevents a system from solving the same problems at different abstraction levels and provides a well-defined criterion for when to backtrack to a higher abstraction level.

GENERATING MONOTONIC ABSTRACTIONS

This section describes an implemented algorithm for producing abstraction spaces, shows that the complexity of the algorithm is n^2 in the number of literals in the domain, and proves that algorithm produces monotonic hierarchies of abstraction spaces.

The Algorithm

The algorithm is given the operators of a domain and it produces a monotonic hierarchy of abstraction spaces. Abstraction spaces are formed by removing sets of literals from the operators and states of a domain. The algorithm is based on the premise that the literals in a domain will only interact with some of the other literals. Thus, the algorithm partitions the literals of a domain into classes and orders them to exploit this structure. This in turn is used to form a hierarchy of abstraction spaces by removing successive classes of literals from a domain. The literals removed at each level only interact with other literals that are in the same class or those already removed from the domain. The final hierarchy consists of an ordered set of abstraction spaces, where the highest level is the most abstract and the lowest level is the most detailed.

The basic algorithm for producing monotonic abstraction spaces is given in Table 1. The operators are given as input and are specified in terms of their preconditions and effects. For this simplified version of the algorithm, the preconditions and effects are restricted to conjunctions of

Input: The set of operators for a domain.
Output: A hierarchy of monotonic abstraction spaces.

```
Create_Abstraction_Hierarchy(OPERATORS)
1. ForEach OP in OPERATORS
      ForEach LIT1 in Effects(OP)
      i. ForEach LIT2 in Effects(OP)
            Add_Directed_Edge(LIT1,LIT2,GRAPH)
      ii. ForEach LIT2 in Preconditions(OP)
            Add_Directed_Edge(LIT1,LIT2,GRAPH)
2. Combine_Strongly_Connected_Components(GRAPH)
3. Topological_Sort(GRAPH)
```

Table 1: Algorithm for Producing Monotonic Abstraction Spaces.

ground literals. (A ground literal is a possibly negated atomic formula that is fully instantiated.) The algorithm forms a directed graph, where the vertices of the graph are the literals and the edges are constraints between literals. A directed edge from one literal to another indicates that the first literal must be higher or at the same level in the abstraction hierarchy as the second literal. The algorithm works as follows:

- Step 1 creates the directed graph from the operators. This step adds constraints that guarantee the achievement of a particular literal could never require adding or deleting a literal higher in the abstraction hierarchy. The constraints force all the effects of an operator into the same abstraction level and force the preconditions of an operator into the same or lower levels as the effects.
- Step 2 combines the strongly connected components of the graph using a depth-first search algorithm described in [Aho *et al.*, 1974]. This step eliminates cycles in the graph by partitioning the literals into classes. The remaining constraints between classes specify the order in which the literal classes can be removed from the domain to form abstraction spaces. Thus, the partially ordered literal classes represent a partial order of abstraction spaces.
- Step 3 transforms the partial order into a total order by performing a topological sort, as described in [Aho *et al.*, 1983]. The total

order can be transformed into an abstraction hierarchy simply by removing the literal classes one by one to form successive abstraction spaces.

An extended version of this algorithm has been implemented in the ALPINE system [Knoblock, 1989]. This extended algorithm handles a more sophisticated language and is more likely to find abstractions than the simple algorithm described above. The language ALPINE handles includes variables, disjunction, quantification, and conditional effects. One problem with the general algorithm is that the constraints may form a single connected component, and the literals will collapse into a single level. However, not all of the constraints generated by the algorithm above are necessary to guarantee monotonicity. ALPINE adds fewer constraints and can thus find additional levels of abstraction in some domains. It uses knowledge about the primary effects of operators to avoid adding unnecessary constraints on the effects. Similarly, it uses domain axioms to prove that particular preconditions will hold under certain contexts to avoid adding unnecessary constraints on the preconditions. In addition, while the algorithm described above produces a single abstraction hierarchy, ALPINE selects the abstraction hierarchy from the partial order based on the problem to be solved.

Complexity of the Algorithm

The worst-case complexity of the algorithm is $O(o * n^2)$, where o is the number of operators in a domain, and n is the number of different instantiated literals. The number of effects and the number of preconditions for any given operator is at most n. Therefore Step 1 of the algorithm is $O(o * n * (n + n))$, which is $O(o * n^2)$. The complexity of finding the strongly connected components of a directed graph is $O(max(e, v))$ [Aho *et al.*, 1974]. The number of vertices v is the number of literals n in the domain. In the worst case there is an edge connecting every pair of vertices, so the number of edges e is at most n^2. Therefore, the complexity of Step 2 is $O(n^2)$. Finally, Step 3, the topological sort, simply requires a depth-first search, $O(max(e, v))$, which is also $O(n^2)$. Since the complexity of the first step is the largest, the worst-case complexity of the algorithm is $O(o * n^2)$.

Proof of Correctness

This section proves that the algorithm described above produces a hierarchy of monotonic abstraction spaces.

Lemma 1 *The algorithm forms a hierarchy of abstraction spaces such that any plan to achieve a literal could not add or delete a literal higher in the hierarchy.*

Proof: A plan to achieve a literal consists of a sequence of operators, where each operator either directly or indirectly achieves the literal. This operator sequence can be viewed as a goal tree that represents the goal/subgoal structure of the plan. For each goal in the tree, there is a corresponding operator in the plan that achieves the goal. The goal literal is at the root of the tree and the last operator in the sequence achieves this goal. The depth of an operator is the number of intermediate goals from the goal the operator achieves to the root of the tree. The proof is by induction over the depth of the operators.

In the base case, consider the operator at depth one that directly achieves the goal. This operator has one or more effects, one of which achieves the goal. Since Step i of the algorithm adds constraints that force all the effects of an operator into the same level in the abstraction hierarchy, none of the effects of the operator could add or delete a literal higher in the hierarchy than the goal literal.

In the inductive case, we show that if none of the operators at depth i could add or delete a literal higher in the hierarchy, then none of the operators at depth $i+1$ could add or delete a literal higher in the hierarchy. The operators at depth $i+1$ achieve preconditions of the operators at depth i. Step ii of the algorithm adds constraints that force the preconditions of an operator to be at the same or lower level as the effects. This guarantees that the precondition that the operators at depth $i+1$ achieve are lower or at the same level as the effects of the operators at depth i. Step i of the algorithm guarantees that the other effects of the operators at depth $i+1$ are at the same level as the effect that achieves the precondition. Thus, all of the effects of the operators at depth $i+1$ are at the same or lower level in the abstraction hierarchy as the effects of operators at depth i. Since the operators at depth i could not add or delete any literals higher in the hierarchy, the operators at depth $i+1$ could not. □

Theorem 1 *The algorithm produces a hierarchy of monotonic abstraction spaces.*

Proof: By definition, a hierarchy of abstraction spaces is monotonic if there exists a solution to a problem, then there exists a solution to that problem in the highest abstraction space and that solution can be monotonically refined into each successive level in the hierarchy.

If a solution to a problem exists, then an abstract plan exists in the highest abstraction space and in all the intermediate abstraction spaces. A problem solution can be transformed into successively more abstract solutions in each abstraction space by deleting those steps that achieve literals that are not in that abstraction space. We prove by contradiction that the resulting solutions will be valid ones, in that every operator in the solution will either directly or indirectly achieve the goal. Assume that one of these resulting solutions is not valid. Then there must be an operator in the solution that is not relevant to achieving the goal. Since the original solution was valid, this operator must have achieved a precondition of one of the deleted operators. This is a contradiction since it follows from Lemma 1 that the precondition of a deleted operator could not depend on a literal higher in the hierarchy.

The abstract solution can be monotonically refined into each successive level in the hierarchy. The abstract plan at each level has a refinement at the level below it, which is the plan that contains the deleted steps. From Lemma 1 it follows that the abstract plan at each level can be refined into the corresponding abstract plan at the lower level without adding or deleting literals higher in the hierarchy. By definition, a refinement is monotonic if it contains the corresponding enablements of the abstract plan. A refinement will certainly have all of the corresponding enablements if none of the literals that comprise the enablements are added or deleted in the refinement process. Thus, there exists an abstract plan at each level of abstraction that has a monotonic refinement at each successive level. □

The next section describes the set of abstraction spaces produced for the Tower of Hanoi puzzle, describes how these abstractions are used for hierarchical planning, and shows that the use of these abstraction spaces reduce the size of the search space from exponential to linear in the length of the solution.

```
(MOVE_DISK3_FROM_PEG2_TO_PEG3
  (preconds ((on disk3 peg2)
             (not (on disk2 peg2))
             (not (on disk1 peg2))
             (not (on disk2 peg3))
             (not (on disk1 peg3))))
  (effects ((not (on disk3 peg2))
            (on disk3 peg3))))
```

Table 2: Example Operator in the Tower of Hanoi Domain.

THE TOWER OF HANOI EXAMPLE

The Tower of Hanoi puzzle has been discussed in a number of papers on reformulation [Amarel, 1984, Ernst, 1969, Korf, 1980]. This section describes how the algorithm for generating monotonic abstraction spaces completely automates one possible reformulation of the Tower of Hanoi domain. This reformulation was previously described in [Korf, 1980], but Korf only described a language for representing reformulations and did not have a technique for finding them.

The Tower of Hanoi puzzle involves moving a pile of different size disks from one peg to another, using an intermediate peg. Only one disk at a time can be moved and a larger disk can never be placed on a smaller disk. This section uses a three-disk puzzle to illustrate the algorithm for producing monotonic abstraction spaces. The axiomatization consists of 18 operators,[7] where there is one operator for moving each disk between every pair of pegs. An example operator for moving disk3 from peg2 to peg3 is shown in Table 2. Note that disk1 is the smallest disk and disk3 is the largest.

The algorithm described in the last section produces a three-level abstraction hierarchy for the three-disk Tower of Hanoi. The algorithm is able to divide the disks into separate levels since a smaller disk can always be moved without interfering with a larger disk. The highest abstraction level includes literals involving only the largest disk. The next level includes both the largest and middle size disk. And the third level includes all three disks. The constraints that the algorithm generates

[7] The extended version of the algorithm handles variables and can produce abstraction spaces for a three-operator version of this domain.

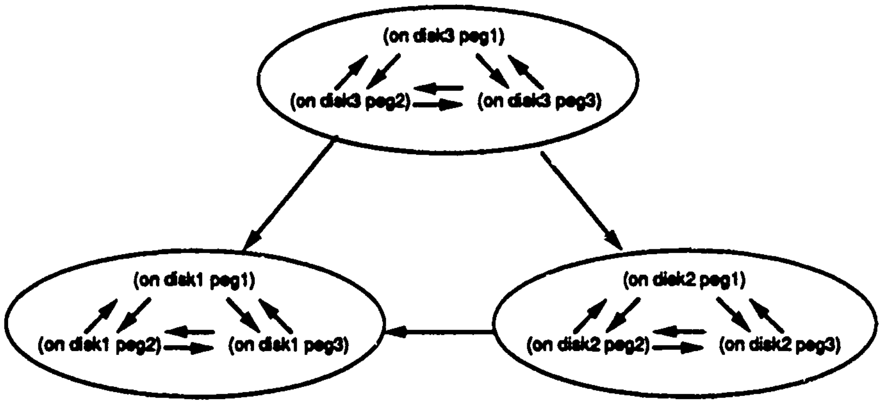

Figure 3: Constraints on the Literals in Tower of Hanoi Domain.

are shown by the arrows in Figure 3. Ovals are placed around connected components in the directed graph to indicate which literals are combined into a literal class. The constraints between levels indicates the order in which the literal classes can be removed to form the abstraction spaces.

Figure 4 shows the hierarchical solution to a three-disk Tower of Hanoi problem. The picture shows the plans produced at each level of abstraction and the mapping between the levels. At the highest level there is simply a one step plan that moves the largest disk from the first peg to the third peg. At the next level this is refined into a three step plan that first achieves the abstract state and then adds the additional step to move the middle disk to the third peg. Finally at the third level, which produces a plan in the base space, each of the intermediate states from the second level form intermediate goals that are solved to produce the final plan.

The algorithm produces an ideal set of abstraction spaces for the Tower of Hanoi domain. Backtracking across abstraction levels or across subproblems within an abstraction level is never required. The abstraction decomposes the problem into subproblems that are all of size two, and the final solution is the shortest one possible. In addition, the ratio between the lengths of the plans at any two levels is two, and the number of levels is $\log_2(l)$, where l is the length of the solution at each level. In general, the solution to an n-disk problem will require 2^n steps, and the number of levels will be n. Since the algorithm forms the optimal

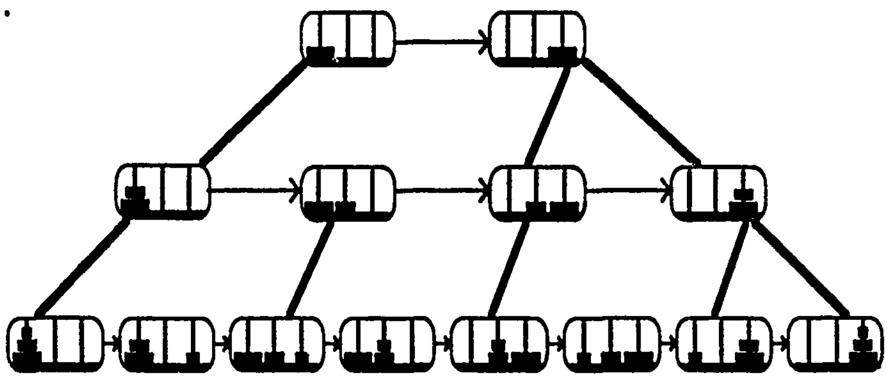

Figure 4: Hierarchical Planning in the Tower of Hanoi.

number of levels for an n-disk problem ($\log_2(2^n) = n$), the ratio between the levels is equal to the base of the logarithm, and all four of the assumptions in the analysis hold, the abstractions in this domain produce the maximum possible reduction in the size of the search space: $O(b^l)$ to $O(l)$.

CONCLUSIONS

This paper shows that hierarchical planning can reduce the size of a search space from exponential to linear in the length of the solution. The Tower of Hanoi puzzle is given as an example domain in which the technique provides an exponential reduction in search. Although more complex domains are not usually as neatly decomposable as the Tower of Hanoi, useful abstractions exist for many interesting domains. The algorithm presented in the paper provides an approach to finding abstractions in domains that are not as well-structured as the Tower of Hanoi, but still have enough structure to be exploited by a hierarchical planner.

An extended version of the algorithm for producing monotonic abstraction spaces is implemented in the ALPINE system. The abstraction spaces produced by ALPINE are used by a version of the PRODIGY problem solver [Minton *et al.*, 1989], extended to plan hierarchically. As described in [Knoblock, 1989], ALPINE was run on the STRIPS robot planning domain [Fikes *et al.*, 1972], and the system produced better abstractions starting with less knowledge than ABSTRIPS [Sacerdoti, 1974]. Work in progress includes extending the system to run on other domains, and integrating the learned abstractions with other types of learning in PRODIGY.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Jaime Carbonell, and Oren Etzioni, Herbert Simon and Manuela Veloso for their comments, suggestions and insights regarding this paper. I would also like to thank Claire Bono and Jeff Schlimmer for their careful reading of the paper.

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THESIS PROPOSAL
Learning and Using Abstractions for Hierarchical Planning

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Abstract

Abstraction has proved to be an effective technique for coping with the large search spaces in planning domains. However, past work has not focused on what constitutes a good abstraction and how to create them. This proposal describes a theory of hierarchical planning which identifies the important properties of abstractions. Within the framework of this theory a system can learn abstraction spaces, represented as abstract state spaces, through domain analysis and problem-solving experience. The learning component generates a partial order of possible abstraction spaces, and later the problem solver dynamically selects a particular abstraction hierarchy based on the characteristics of the problem to be solved. The PRODIGY problem solver will be extended to use the selected abstraction hierarchies to create abstract plans and then refine these plans into progressively more detailed ones. Initial prototypes of both the abstraction learning and planning components have already been built and the full system described in this proposal will be implemented and tested on several different domains for the thesis.

*The author is supported by a graduate fellowship from Universal Energy Systems, Inc. under subcontract number S-789-000-037. This research was sponsored in part by the Office of Naval Research under contract number N00014-84-K-0415, and in part by the Defense Advanced Research Projects Agency (DOD), ARPA Order No. 4976, Amendment 20, under contract number F33615-87-C-1499. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressed or implied, of the Office of Naval Research, the Defense Advanced Research Projects Agency or the US Government.

Contents

1 Introduction

Abstraction is an effective technique for reducing the often unwieldy search spaces involved in problem solving.[1] In particular, hierarchical planning can significantly simplify a problem by first solving it at an abstract level and then using the resulting abstract plan to decompose the problem into a number of smaller subproblems. Each step in the abstract plan is then refined at progressively more detailed levels until the problem is solved in the ground space. Hierarchical planning is useful because a problem can first be solved in a simpler abstract space and the resulting solution is then used to guide the search for a solution to the original problem. This technique reduces the complexity of the problem since the total cost is the sum of the costs of each of the individual searches, not the product[14,17].

The abstractions used by existing problem solvers can be roughly categorized as one of two types, which Doyle describes in [5]. The first is called *approximation*. An approximate abstraction is one that eliminates detail by ignoring certain conditions or constraints. For example, ABSTRIPS[24] uses approximation since it creates a new approximate theory by dropping some of the preconditions of the operators. Approximate abstractions are useful because a problem can often be modeled by a simpler problem that is easier to solve. The solution to the simpler problem can then be used to guide the solution to the harder problem.

The second type of abstraction is *aggregation*. An aggregate abstraction involves a change in the granularity of the objects. Aggregate objects are usually formed by combining simpler structures into more complex ones. For example, a house can be viewed as composed of rooms, and planning paths within a house requires deciding on a sequence of rooms to move through. The same house can also be viewed at a more detailed level where each room is composed of many individual locations. Here planning paths within a house requires determining a sequence of locations that achieves a goal. Depending on the size of these locations, planning at this level could be a considerably more difficult problem. A good way to solve this problem is to make use of the structure of the domain and plan at the level of rooms first and then use that plan to find a more detailed plan at the level of locations.

Both forms of abstraction arise in the work described here. Approximation is the primary technique used to create abstraction spaces. However, if a domain contains objects represented at several different levels (e.g., rooms and locations within rooms), then the system can produce aggregate abstractions through approximation. In addition, approximation allows similar operators or objects that are indistinguishable at an abstract level to be combined into abstract operators or groups of abstract objects.

Previous work on abstraction in planning has primarily focused on the use of abstraction to reduce search. Little work has focused on how these abstractions are created and what constitutes a useful abstraction. This thesis addresses the problems of automatically creating and using abstraction spaces for hierarchical planning in operator-based planning systems.

[1] The terms planning and problem solving are used interchangeably throughout this proposal.

1.1 Terminology

This section defines both the planning and hierarchical planning terminology.

1.1.1 Planning

Operators: *Operators* specify the legal transformations from one state to another. An operator consists of *preconditions*, which specify the conditions that must hold in order to apply an operator, and *effects*, which specify how the world will be changed as a result of applying an operator. The effects consist of *adds* and *deletes*, which specify the formulas that will be added and deleted from the state, respectively. The *primary adds* of an operator are the conditions that an operator will be used to achieve, while the *secondary adds* are side effects.

Objects: *Objects* are the elements in the world that can be manipulated by the operators. The properties and relations on objects are specified in the initial state.

States: *States* are conjunctive formulas that represent models of the world. A planning problem consists of an *initial state* and a *goal state*, which specify the initial configuration and the desired configuration of the world. Note that a goal state is only a partial specification of the final state and often consists of a number of individual *goals* (conjuncts).

Plans: *Plans* are sequences of operators that transform an initial state into a goal state.

Domains: *Domains* consist of the operators, objects, states and plans for a class of planning problems.

1.1.2 Hierarchical Planning

Abstraction: *Abstraction* is used to refer to an approximation or simplification. The term usually refers to operators, objects, states, plans, or domains.

Abstract operator: An *abstract operator* is a simplified operator, which is formed by removing predicates from both the preconditions and effects.

Abstraction space: An *abstraction space* consists of a set of abstract operators that define a problem space.

Abstraction level: An *abstraction level* is the same as an *abstraction space*. Moving up an abstraction level refers to moving to a more abstract level and moving down is moving to a more concrete abstraction level. The *ground space* is the most detailed space.

Abstract plan: An *abstract plan* is a plan created using an abstraction space.

Abstraction hierarchy: An *abstraction hierarchy* refers to a set of abstraction spaces that are arranged in a total order. For a given domain there often exists a number of different abstraction hierarchies.

1.2 Outline

The outline of the proposal is as follows. The next section states the objectives of the thesis. Section 2 describes a theory of hierarchical planning which forms the basis for the rest of this work. This theory identifies the *noninteraction* and *achievability* properties which determine whether an abstract solution can be expanded into a detailed solution. Section 3 describes the state space representation of an abstraction space. Section 4 argues that an abstraction hierarchy should by dynamically selected for each problem to be solved. Section 5 describes the techniques for learning abstraction spaces. Section 6 explains how a particular abstraction hierarchy is then selected and used in planning. Section 7 evaluates the costs and tradeoffs of learning and using abstractions. Section 8 describes the related work on abstraction and hierarchical planning. Finally, section 9 presents the research plan and section 10 describes the contributions of the thesis.

1.3 Thesis Objectives

This thesis will address the issues of representing, learning and using abstraction spaces for hierarchical planning. Addressing these issues involves understanding what the properties of a useful abstraction are, how abstractions with these properties can be represented, how they can be learned, and how they can be used by a problem solver. The thesis will provide a theory of abstraction spaces, describe one possible representation, and develop techniques and algorithms for learning abstraction spaces and planning with them. My thesis is that *noninteraction* and *achievability* are the critical properties of an abstract plan and can be used to generate effective abstraction spaces for hierarchical planning.

To demonstrate the thesis I will implement a system for learning abstraction spaces that is based on the noninteraction and achievability properties and then extend the PRODIGY architecture to plan using these abstractions. The resulting system for both learning and using abstractions will then be tested on three or four planning domains. The measure of success will be the ability to produce abstractions that improve performance over the same domain without abstraction. Performance improvement will be measured in terms of the solution time and solution quality, or the time required to determine that no solution exists.

2 Towards a Theory of Hierarchical Planning

Hierarchical planning involves creating an abstract plan and using that abstract plan to guide the planning of the problem in the ground problem space. The abstract solution is used to create a number of smaller subproblems, effectively creating islands in the search space. Figure 1 shows a two-level hierarchical plan. In this example, the problem can be solved in the abstract space in two steps. This in turn creates two subproblems in the ground space. The precise mapping from a step in an abstract plan to the corresponding subproblem may vary. In some cases it involves finding a sequence of operators in the ground space that map from one abstract state to another. In other cases it involves achieving additional preconditions that were not checked in the abstract operators. Then each of the individual subproblems are solved to produce a solution to the original problem. The following sections describe the two basic problems that can arise in this mapping and

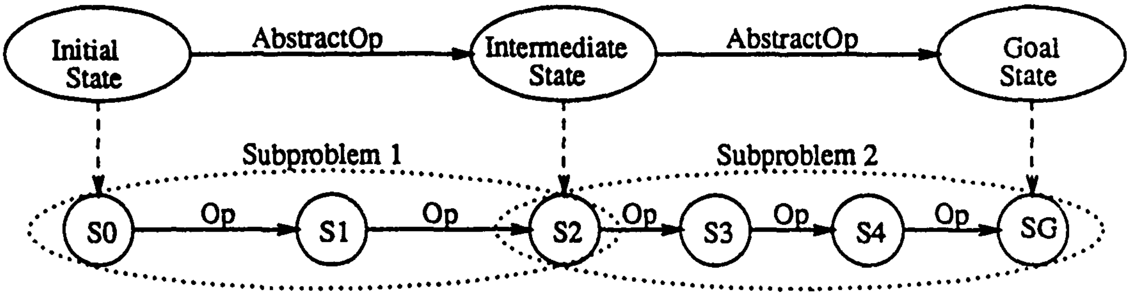

Figure 1: Hierarchical Planning

define the corresponding properties of an abstract plan, *noninteraction* and *achievability*, such that if the properties hold, the problems will not arise. Thus, the properties determine the effectiveness of abstract plans, which in turn determines the utility of the abstraction spaces that produce the plans.

2.1 Noninteraction

An abstraction should capture the structure of a problem domain, separating out the details from the important aspects. For example, in path planning for a household robot, one could plan a path from room to room, and once this problem is solved, plan the detailed paths within the rooms. A desirable feature of this abstraction space is that in the process of planning the detailed paths, the abstract p' ·· is not altered. The invariance of the abstract plan is important because the abstract solution ı. used to guide the search for a solution at the next level of detail. An abstract plan is said to be *noninteracting* if the plan is not invalidated in the process of expanding the plan in the more detailed abstraction spaces, or more precisely, if the literals satisfying the preconditions of the abstract operators are not undone in the process of refining the abstract plan.

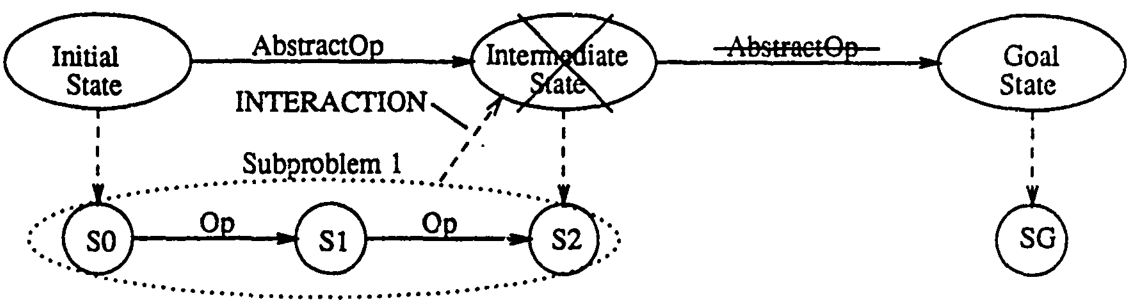

Figure 2: An Interaction Problem

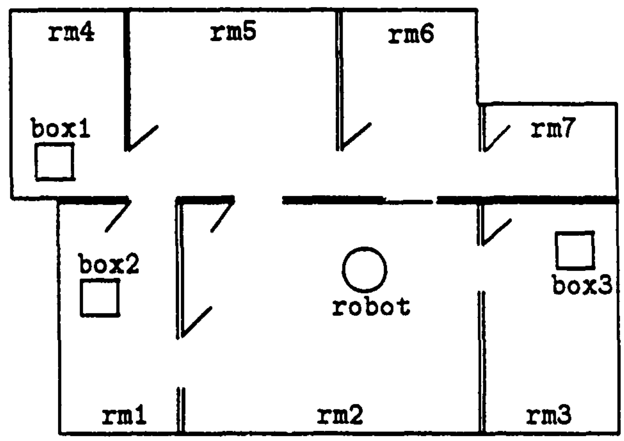

Figure 3: Robot Planning Domain

Figure 2 illustrates a violation of the noninteraction property where an operator used to solve a subproblem somehow violates the conditions that must hold in order for an abstract operator to be applicable.

Consider the simple STRIPS[9] robot planning domain shown in Figure 3. In this domain there are several rooms, a robot, a small set of blocks, and doors between connecting rooms which can be open or closed. In the formulation of this problem, there are operators for moving the robot between adjacent rooms, next to a box, next to a door, and to a particular coordinate location. Similarly, there are operators for moving boxes between rooms, next to another box, next to a door, and to a particular location. There are also operators for opening and closing the doors.

A problem in this domain might be to place several blocks next to each other in a particular room. A useful abstract plan to solve this problem might only consider moving blocks among rooms, ignoring the placement within a room, the path of the robot, or whether the doors are open or closed. The abstract plan could then be expanded to include moving the robot to each room that contains a box to be moved. Eventually, the plan would be refined down to the ground space and all of the details would be considered.

This example illustrates the noninteraction property. At an abstract level, a plan is produced that only specifies which rooms the blocks are to be pushed through. This abstract plan is noninteracting since once the plan for moving between rooms has been produced, the expansion of the details cannot interfere with the abstract plan. Once the paths for the blocks have been determined, that part of the plan is considered fixed and is then used to expand the rest of the details. If an abstract plan did not have the noninteraction property, planning in the more concrete space might invalidate the abstract plan, thus eliminating any savings in search and possibly making the cost of planning with abstraction more expensive than planning without it.

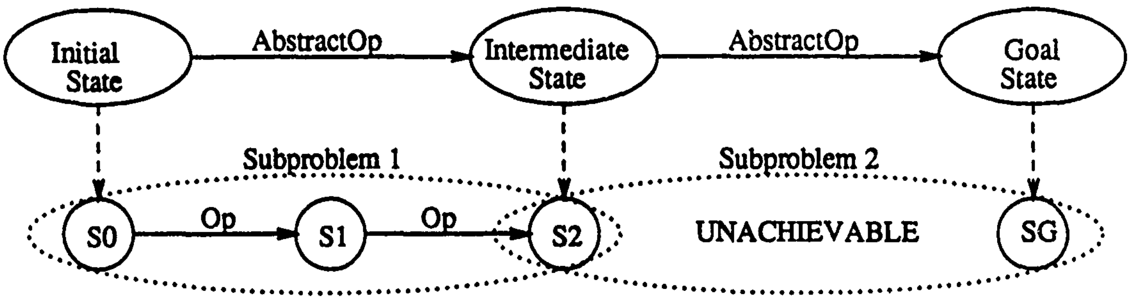

Figure 4: An Achievability Problem

2.2 Achievability

The noninteraction property, although important, is not sufficient to guarantee the utility of an abstract plan. The existence of an abstract plan does not guarantee that there is a corresponding detailed solution to the problem. This is because an operator may be applicable in an abstract space, but the conditions ignored in the abstract space might not be achievable in the ground space. An abstract plan is ***achievable*** if there is a way to refine the details such that there is a corresponding plan in the ground space. The achievability of an abstract plan depends on the achievability of the individual operators, which in turn depends on the static preconditions of the operators. The static preconditions are properties of the domain that cannot be changed. Since the truth of the static preconditions depends on the initial state, achievability can vary from one problem to another. Figure 4 illustrates an achievability problem where an abstract plan exists but it is not achievable.

Returning to the example, in planning the paths for the boxes at the abstract level, the status of the doors (i.e., open or closed) is ignored. If a door can always be opened, then a plan produced in this abstract space will be achievable. However, if some of the doors could be locked with no way to unlock them, then a plan produced at the abstract level may be unachievable. Moreover, if doors are often found locked, then whether or not a door is open is not a mere detail, but an important consideration that should be taken into account when the path through the rooms is planned. On the other hand, if the doors are almost never locked, then ignoring the status of the doors might still be a useful abstraction. In the few cases where a locked door causes a planning failure, the planner simply backtracks across abstraction levels and plans an alternate path.

A property closely related to the achievability of the abstract plan is the independence of the subproblems generated by the plan. Subproblems are independent if all of the subproblems generated by an abstract plan can be solved regardless of the way the other subproblems are solved. Minsky[17] and Korf[14] both claim that the power of abstraction comes from the fact that an abstract plan divides up a problem into a number of subproblems where the cost of solving the original problem is the sum of the cost of solving the subproblems, rather than the product. However, this analysis assumes that the subproblems are independent. If they are independent, then a failure in achieving a particular subproblem only requires backtracking to a higher abstraction space. In contrast, if they are not independent, then a failure will first require backtracking to the other subproblems and then require backtracking across abstraction levels. If an entire problem is unsolvable because of a particular subproblem, that can be determined much faster if the subproblems are independent.

3 Representing Abstraction Spaces

There are a number of ways abstraction spaces can be represented for use in planning. Operators, goals, states, and objects can all be simplified in various ways. ABSTRIPS ignored certain preconditions of the operators, GPS[21] ignored some of the differences between states, and in Korf's work[14] on abstraction, states are mapped into abstract states. In this work, the last approach is used. However, it is important to note that the properties described in the last section apply equally well to other possible abstraction space representations. In fact, in previous work[13], which shows how the noninteraction property can be used to reproduce the results in the ABSTRIPS paper, I describe a system that automatically creates abstraction spaces by dropping preconditions. This section describes the motivation for choosing the state-space representation, as well as how this representation allows the system to form a hierarchy of abstract operators and objects.

In ABSTRIPS, abstraction spaces are represented simply by assigning criticalities to the preconditions of each operator. There are a number problems with this approach. First, as pointed out by Tenenberg[31], there is no clear semantics for operators or states. The operator's effects are not abstracted as are the preconditions, so the system can arrive at inconsistent states, which may or may not be a problem depending on the particular inference mechanisms used. Also, without a well-defined semantics it is difficult to separate the representation of the abstraction from the control structure of the problem solver. Second, simply dropping the preconditions of an operator does not allow operators or objects that are indistinguishable at an abstract level to be combined into a single operator or object. For example, consider the case where there are two operators that only differ by a few preconditions and effects. If those differences are details, then ideally the system could combine those operators into a single abstract operator. However, if the preconditions are identical but the effects differ, then it is not clear what the effects of the abstract operator should be.

A more systematic approach to representing abstractions is to completely remove certain properties or relations from the domain. Thus, a set of states is mapped into a single abstract state. For example, if the status of a door is shown to be a detail in some abstraction space (as described in Section 5), then all of the predicates concerning the door status are removed from the operators, objects and states in that space. Removing properties from the domain has the effect of creating a simpler domain theory in which to plan and learn. Simplifying the operators, objects, and initial states is straightforward, but simplifying the goal states is a bit tricky since the goals are not known when the abstractions are created. A goal state could violate the noninteraction property if a conjunct of a goal state is removed and added back during the refinement of an abstract plan. Section 4 describes an approach to abstracting goal states and selecting appropriate abstraction spaces that prevent compound goals from violating the noninteraction property.

Creating abstractions at the granularity of the domain predicates[2] has several important advantages. First, as in Korf's model of abstraction[14], an abstraction is simply a mapping from one state space into a simpler state space. For example, removing predicates involving door status maps all of the states that differ by the status of one or more doors into the same state. Thus, the simpler space can be used to discover interactions or failures without the overhead of the more detailed space. Second, operators that are different in the ground space, but are indistinguishable at an abstract space, can be mapped into a single abstract operator. Abstract operators can provide a considerable reduction in search. Without abstraction, if a plan fails using one operator, another similar operator may be tried which will probably fail for the same reason. An abstract operator contains the common parts of two or more operators so if a failure occurs at the abstract level each of the individual operators will not need to be tried. Third, objects that are indistinguishable at an abstract level can be treated as a class of objects instead of being reasoned about individually during planning. Thus, if planning fails using one object in a class, attempting the same plan with another object from the same class will also fail. Fourth, a simpler state space makes the job of a learning system easier and more effective. An explanation-based learning system would have fewer details to deal with, and an analogical learner could store the more abstract plans which would be applicable to a wider range of problems.

4 Selecting Abstraction Spaces

An important aspect of abstraction is knowing under what circumstances one can use an abstraction. Useful abstraction spaces cannot be determined from the domain alone, but, instead must be based on the problem to be solved. In the previous work on hierarchical planning, either the planner chooses an abstraction hierarchy and then maps the goals into the highest abstraction space[21,24,25,31] or the user specifies goals that are in the highest abstraction level[27]. This section describes the problem with selecting a hierarchy before the goal states are given and then outlines a method for choosing an abstraction hierarchy based on the goals to be solved.

ABSTRIPS maps a goal state into the corresponding abstract operators that achieve the individual goals. This works for goal states that consist of a single conjunct, but for more complex goal states there could be interactions between the goals which could cause an interaction across abstraction levels. For example, consider the example domain shown in Figure 3 and a goal state that involves two goals: `(and (closed door23)(in-room robot room3))`. In order to solve the first goal of having `door23` closed the robot would need to be in one of the rooms adjacent to the door. Doors are named by the rooms they connect, so the robot would need to be in either `room2` or `room3` to close the door. And, the robot must pass through `door23` to achieve the second goal of being in `room3`. A problem now arises if the status of the doors is abstracted from the operators

[2]The system produces more detailed abstraction spaces by requiring the domain implementor to add explicit types to the objects in a domain. For example, `(in-room object2 room5)` is distinct from `(in-room robot1 room2)` because `object2` is of type object and `robot1` is of type robot. This is equivalent to having two different predicates (e.g., `ObjectInRoom` and `RobotInRoom`). Explicit typing allows predicates with different argument types to be placed at different abstraction levels. Throughout the rest of this paper, types are used as place-holders for arguments in a predicate, and, in discussions about predicates, a predicate with arguments with more than one possible type are considered to be separate predicates.

and states, but goals involving the door status are allowed. The robot might plan to close door23 from room2, then go into room3. Since door status has been removed at the abstract level, when the robot plans to go into room3, it ignores whether the door is open or not and will not notice that the other goal just achieved will be violated. The problem will be detected when the abstraction level involving door status is reached and arises because the goal states are not abstracted with the rest of the domain.

Another approach to mapping goal states into the most abstract space is to delay the consideration of goals that refer to predicates lower in the abstraction hierarchy. This is the approach taken by Tenenberg[31] in his formalization of ABSTRIPS. A different problem arises now which also involves an interaction between the top-level goals. Consider a problem similar to the one above, except the goals are to close door45 and go to room3. Assuming the same abstraction as above, the problem would be solved at an abstract level involving only the goal involving in-room. So the robot would move from room2 to room3, ignoring the goal of closing door45. Then, when the level of abstraction is reached involving the door status, a path would need to be planned to get to that door, invalidating the plan to achieve the first goal. This, of course, is exactly the type of interaction between abstraction levels which one would like to avoid because now the goal of getting the robot in room3 would have to be reachieved.

An approach to this problem that does not violate the noninteraction property is to dynamically select an abstraction hierarchy based on the problem. First, the goal states are simplified and mapped into more abstract goal states where there is no possibility of an interaction. Then an abstraction hierarchy is chosen such that the goal state cannot generate interactions across abstraction levels. In this example, the predicates involving door status could be elevated to the same level in the hierarchy as the predicates involving the robot location. Thus, the possible interactions between these goals would be detected and resolved at a single abstraction level. The details of abstracting goal states and selecting an abstraction hierarchy are described in Section 6.1.

5 Learning Abstraction Spaces

Ideally the system should form abstractions based on the problems to solved, however, it would be costly and repetitive to form the abstractions in a domain as each problem is given. Instead, the learning system creates a partial order of abstraction spaces that are guaranteed to produce noninteracting abstract plans for goal states consisting of a single goal. Then when an actual goal state is given, the system can select an abstraction hierarchy from the partial order that guarantees the noninteraction property for all of the goals in the goal state.

This section describes how the system can automatically derive a partial order of abstraction spaces. The final partial order represents a set of abstraction spaces that the system has tested for both noninteraction and achievability. A total ordering of this set specifies one possible abstraction hierarchy. To produce the partial order for a domain, first, the operator's effects are analyzed to derive an initial partial order that is necessary, but not sufficient to guarantee the noninteraction property. Since the initial partial order may be highly under-constrained, the system uses problem-solving traces to generate candidate abstractions that are likely to produce plans without noninteraction or achievability problems. The system uses these candidate abstractions to refine

PREDICATES	OPERATORS push thru door	crry thru door	go thru door	open door	clse door	lock door	un-lock door	push to door	push to obj	put down nxto	pick up	put down	goto door	goto obj
(in-room obj room)	A,D	A,D												
(in-room robot room)	S,D	S,D	A,D											
(opened door)				A	D									
(closed door)				D	A									
(locked door)						A	D							
(unlocked door)						D	A							
(holding object)										D	A	D		
(armempty)										S	D	A		
(next-to obj door)	D							A,D	D		D			
(next-to obj obj)	D							D	A,D	A	D			
(next-to robot door)	D	D	D					D	D				A,D	D
(next-to robot obj)	S,D	D	D					S,D	D	S	D	S	D	A,D

A = Primary Add S = Secondary Add D = Delete

Table 1: Table of Connections

the initial partial order into a noninteracting partial order. The noninteracting partial order guarantees that every abstraction space that it defines will produce noninteracting plans for solving single-conjunct goals. Finally, the system empirically tests the achievability of the plans produced in each abstract space.

Throughout this section an example robot planning domain is used to illustrate the techniques. This domain is taken from Minton[18] and is an extended version of the original STRIPS domain[9] and consists of a robot, boxes, rooms, and doors connecting the rooms. The robot can move around the rooms, push the boxes around the rooms, and open and close the doors. In addition, the domain includes locks on doors and keys for the locks. The objects in this domain can be picked up and carried in addition to pushing them. Solving problems in this domain is difficult for several reasons. First, in many cases there appear to be several different ways to achieve the same effects, but not all of them will work for any given situation. Second, since doors can have locks and the robot may not be holding the keys, achievability problems can arise. Appendix B contains the operators for the robot planning domain. The techniques are not specific to this domain and will be tested on several other domains including the machine-shop scheduling domain described in Appendix A.

5.1 Constraints on Abstraction Spaces

In this section the system analyzes the operator's effects to determine which predicates should be grouped together and how the groups should be ordered to form abstraction spaces that produce noninteracting plans. The purpose of this step is to avoid noninteraction problems that are due to side effects of applying operators.

The first step is to determine the interrelationships between the predicates such that it would be impossible to abstract one and not the other. The system combines these predicates into groups that must be placed at the same abstraction level based on interactions between the adds and deletes of the operators. Table 1 shows all of the adds and deletes in the example domain. The table lists the operators across the top and the nonstatic predicates along the left side. Each entry in the table indicates the effect of an operator on a particular predicate. An 'A' indicates that

Predicates	Group Names
(in-room obj room)	ObjectInRoom
(in-room robot room)	RobotInRoom
(opened door) (closed door)	DoorStatus
(locked door) (unlocked door)	LockStatus
(holding obj) (armempty) (next-to obj door) (next-to obj obj)	ObjectLocation
(next-to robot door) (next-to robot obj)	RobotLocation

Table 2: Strongly Interacting Groups

the predicate is a primary add of the operator, an 'S' indicates it is a secondary add,[3] and a 'D' indicates the predicate is deleted by the operator.

The system combines predicates into groups based on strong interactions. Two predicates are *strongly interacting* if there are two operators such that one operator adds the first predicate and deletes the second and the other operator deletes the first and adds the second. For example, the two predicates in the table, (opened door) and (closed door), are strongly interacting. The system combines the predicates in the table into the six groups shown in Table 2. The strong interaction property is transitive and thus the group called ObjectLocation contains four predicates.

A predicate *weakly interacts* with another predicate if an operator that adds the first predicate also deletes the other predicate. The second step in the algorithm is to produce a partial ordering on the groups by looking for weak interactions among predicates. This property is asymmetric and relates to strong interaction in that two predicates strongly interact if there is a weak interaction in both directions. One only needs to consider weak interactions between predicates in different groups since the weak interactions are used to create a partial order on the groups. A predicate that weakly interacts with another predicate is ordered above that predicate in the partial order. In the case of a cycle among groups, the groups are collapsed into a single group. Placing weakly interacting predicates at the same or higher levels of abstraction than the predicates they interact with prevents an operator from undoing (via the effects) predicates that have already been achieved at a higher level of abstraction.

In the example domain there are a number of weak interactions. In Table 1, any predicate that weakly interacts with a predicate in another group will create a constraint on the ordering of

[3]A secondary add is a side effect of an operator. and the implementor specifies which adds are primary and which adds are secondary for each operator. Secondary adds are handled like deletes since secondary adds and deletes are both side effects.

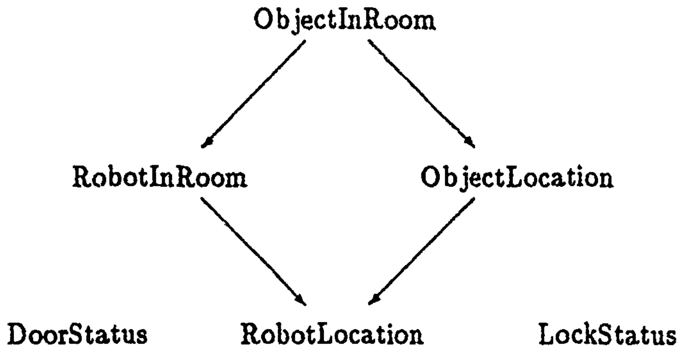

Figure 5: Initial Partial Order

the groups. For example, the predicate (in-room object room) weakly interacts with (in-room robot room) since the first predicate is added by PushThruDoor and the second predicate is deleted by the same group of operators. Therefore (in-room object room) should be higher (or at the same level) in the abstraction hierarchy than (in-room robot room). Consider what would happen if this constraint were violated. The planner might solve a goal of getting the robot into a particular room and then at a lower level of abstraction, in the process of putting an object in a particular room, the system would also change the location of the robot. This violates the noninteraction property between levels of abstraction. The partial order created from the weak interactions is shown in Figure 5. Note that the groups DoorStatus and LockStatus do not interact with any of the other groups.

5.2 Generating Candidate Abstraction Spaces

So far, the system has derived a necessary, but not sufficient, set of constraints for noninteraction since only the operator's effects have been analyzed. The constraints form an initial partial order of the possible abstraction hierarchies, but this partial order is under-constrained and makes no guarantees about noninteraction or achievability. The next step is to find abstraction spaces that produce noninteracting plans. To show that an abstraction space only produces noninteracting plans, the system needs to show that if a predicate group is removed, and then the system produces a plan using the resulting abstraction space, then the abstracted details can be added back into the plan without disturbing the abstract plan. Unfortunately, this condition is often difficult to guarantee.

One obstacle to finding noninteracting abstractions is that the operators only partially or indirectly specify the conditions that must hold for it to be applied. For example, in order for the robot to move through a door, the door must be open. And in turn, in order to open the door it must be unlocked. However, what happens if the door is already open? Does that mean it is unlocked? In this case, yes, but this is a piece of domain knowledge that is not explicitly represented in the operators. This type of knowledge is often necessary for finding noninteracting abstractions in a domain.

Even if all of the appropriate knowledge about the operators is provided, a problem remains: the number of possible abstraction spaces can be quite large and a great deal of effort may be required to show that a particular abstraction space only produces noninteracting plans. Therefore, simply attempting to find good abstraction spaces through brute-force search could be combinatorially explosive.

A method for finding abstraction spaces that addresses the problems of insufficient knowledge and large search spaces is to use problem-solving traces to generate candidate abstraction spaces. These candidate spaces can then be tested to determine if the resulting plans will be noninteracting and achievable. This approach has several advantages. First, since the problem-solving traces presumably represent the type of problems that are going to be solved, the abstractions generated from the traces are more likely to be useful. Second, the traces will considerably reduce the search since the candidate abstractions generated from the traces are much more likely to produce plans with the desired properties than arbitrarily selecting a set of predicates to abstract. Third, the trace-generated abstraction spaces are less likely to produces plans with achievability problems since such problems will often be apparent in the traces. Fourth, if there is not sufficient information about the domain, then the traces can be used to provide a focused method for acquiring additional knowledge.

The system uses problem-solving traces to generate candidate abstractions spaces as follows: First, some simple problems are selected which represent the type of goals and initial configurations that are going to be given. These problems are then solved without any form of abstraction. The solution traces are then examined and a small set of heuristics are used to select candidate abstraction spaces that would have simplified the particular problems under consideration. Abstraction proposing heuristics include pruning leaves and branches and simplifying loops without altering the basic structure of the solution.

Consider the problem-solving trace shown in Figure 6. This is a sketch of a simple problem-solving trace that involves moving an object from one room to another. The door between the rooms is closed and so the robot first goes to the door and opens the door and then goes to the block and pushes it into the other room. The partial order produced in the last section did not provide any information about how the `DoorStatus` group related to the rest of the domain. However, the trace indicates that opening a door subgoals on getting the robot next to the door, so `RobotLocation` will probably have to be placed below or at the same level as `DoorStatus` in the abstraction hierarchy. The candidate abstraction spaces are then tested for noninteraction as described in the next section. Once the `RobotLocation` group has been removed from the domain, then removing `DoorStatus` would be proposed as the next candidate abstraction since the predicates in that group only occur on the leaves of the trace. This process continues until the system has refined the initial partial order into a noninteracting partial order.

5.3 Refining the Partial Order of Abstraction Spaces

In this step the operator's preconditions are analyzed to determine what additional constraints the system needs to add to the partial order such that all of the plans produced by the abstraction spaces are noninteracting. Intuitively, the system adds additional constraints to guarantee that

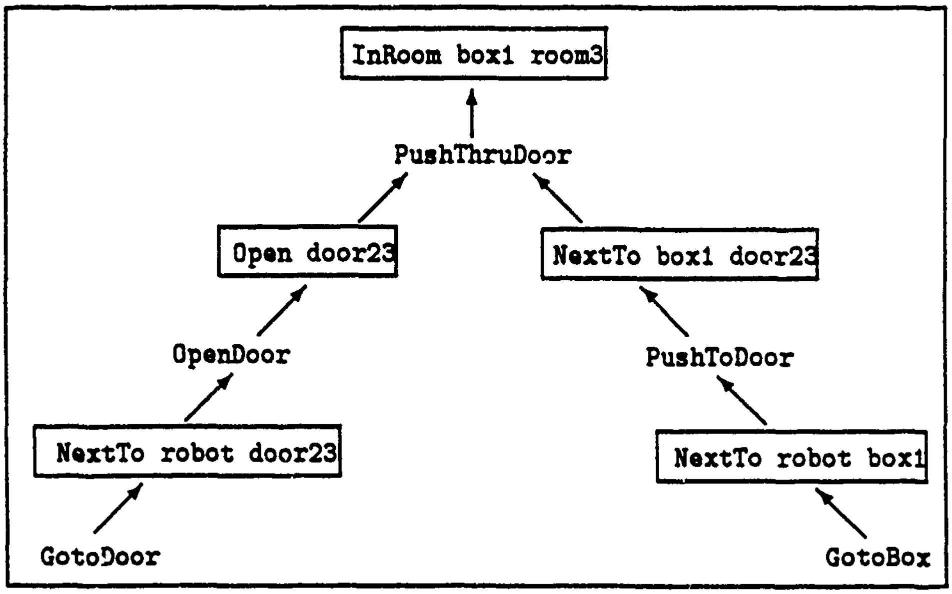

Figure 6: Problem-Solving Trace

any properties that are achieved at a higher abstraction space will never be subgoaled on in a lower abstraction space. This prevents the preconditions from causing an noninteraction problem by generating a goal that might undo something already achieved in a higher abstract space.

The system uses the candidate abstraction spaces described in the previous section to add additional constraints to the initial partial order such that all of the plans produced by the abstraction spaces are noninteracting. The partial order is refined by starting at the bottom of the partial order and attempting to show that each of the candidate abstraction spaces that results from removing a group of predicates produces noninteracting plans. If the system can prove that a candidate abstraction space only produces noninteracting plans, the dependencies in the proof are used to determine what, if any, additional constraints the system needs to add to the partial order. Thus, instead of producing a total order which would depend on the order the examples are given, the system generalizes the ordering of the abstraction spaces by analyzing the dependencies.

The system determines whether a group of predicates can be removed such that the resulting abstraction space produces noninteracting plans as follows. Each predicate in the group is considered in turn. The predicate under consideration, $pred_1$, is tested to determine if it could generate a subgoal higher in the abstraction hierarchy when it is used in planning. To determine this, the system examines the preconditions of the operators that add $pred_1$. These preconditions are the subgoals that could be generated if $pred_1$ does not hold. The system must determine if these preconditions could ever generate a subgoal higher in the abstraction hierarchy. There are a several conditions under which a precondition will not generate a subgoal higher in the abstraction hierarchy:

1. The precondition occurs in a group that has already been placed below this group in the partial order. Therefore, it has already been proved that the precondition will not generate a subgoal higher in the abstraction hierarchy.

2. The precondition occurs in the group under consideration. In this case it will not cause an interaction since all of the predicates in a group are considered at the same level.

3. The precondition, call it $pred_2$, occurs in a group which is not lower or at the same level in the partial order, but will not be subgoaled on because it is true whenever the operator is used in planning to achieve $pred_1$. For example, $pred_2$ will hold if is tested in the preconditions of the operators that contain $pred_1$ as a precondition.

4. The precondition is never subgoaled on due to certain properties of the domain. For example, the operator for opening a door could have a precondition that the door is closed, which will always hold when the operator is considered.

If the above tests are insufficient to prove that an abstraction space is noninteracting, there are several techniques that can be used to force the noninteraction property to hold:

- Add additional constraints to place a group of predicates below another group in the partial order in order to force case 1 above to hold.

- Force a predicate, $pred_2$, to hold by adding it as a precondition to the operator that subgoaled on $pred_1$. To make such a replacement, without changing the semantics of the domain, may require additional knowledge about the relationships between the various predicates.

- Merge the group containing $pred_1$ with the group containing the predicate that could potentially cause an interaction (i.e., put them on the same abstraction level).

Once the system proves that a group of predicates can be removed to form an abstraction space that produces noninteracting plans, then the next step is to determine how that group fits into the partial order. This is done by determining the dependencies for the proof and converting those dependencies into constraints on the partial order. There are two types of dependencies in the proof. First, a group of predicates may need to be placed below another group in the partial order in order to avoid possible interactions. These constraints are simply added to the partial order. Second, in the process of proving that a group will not generate an interaction it may be necessary to use the fact that certain preconditions of operators always hold within particular contexts (as described in case 3 above). Such groups are placed below the groups that provide the necessary contexts.

Consider the following example: the system has already checked the abstraction spaces that result from dropping `DoorStatus`, `RobotLocation` and `ObjectLocation` and the groups have been placed appropriately in the partial order. `RobotInRoom` is generated as the next group to remove to form a candidate abstraction space. `RobotInRoom` can be removed by proving that removing

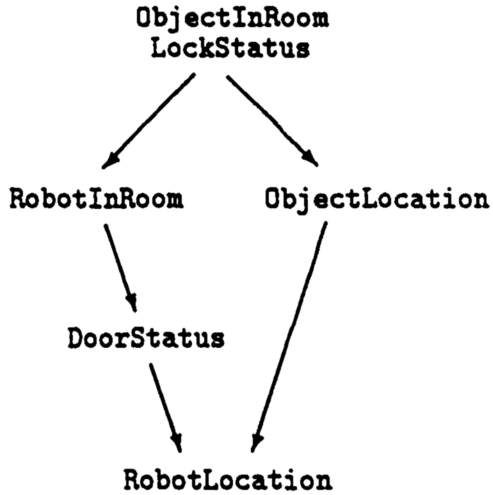

Figure 7: Partial Order of Noninteracting Abstraction Spaces

the predicates in that group will not result in subgoals in a higher abstraction space when those conditions are restored to the plan. This group has only one predicate, `(in-room robot room)`. The system must check the preconditions of the operators that are used to achieve this predicate (i.e., `GoThruDr`). There are only two nonstatic preconditions. The first, `(open door)` has already been placed lower in the partial order. The second, `(in-room robot room)`, is in the group under consideration. Therefore, `(in-room robot room)` can be placed at a separate level in the partial order, as shown in Figure 7.

5.4 Evaluating the Achievability of Abstraction Spaces

After the system has generated an abstraction space, checked it for noninteraction and placed it in the partial order, the system then tests the plans produced in that abstraction space for achievability. The system first tests each proposed abstraction space on the problem that proposed it. If the proposed abstraction space works successfully on the generating problem, it is then tested on other problems to determine its general utility. The writer of the domain provides a set of test problems that represent a "good" cross section of the type of problems that will be solved. The system tests the abstraction space on each of these problems and records the success or failure. If the abstraction space is useful for all of the problems, then the system stores it for future use. If there are achievability problems then the system attempts to determine the cause. If it can determine the cause, it may be possible to elevate the cause of failure to a higher abstraction level. If it cannot determine the cause, then the abstraction space is collapsed with the level above it in order to detect the problem earlier.

5.5 Implementation Status

I have already implemented an initial prototype of the work in this section. The prototype includes the algorithms described in Sections 5.1 and 5.3 and is fully described in [13]. This prototype attempts to produce every possible abstraction hierarchy and assumes that the axiomatization of the domain is completely and correctly specified. Unfortunately, the number of possible hierarchies is quite large and additional domain knowledge is required to find the useful abstractions. The techniques described in section 5.2 provide additional information through examples to aid in the creation of the abstraction hierarchies.

The implemented prototype has been successfully run on the ABSTRIPS problem domain[24]. The algorithm produces a finer grained abstraction hierarchy than the one used in ABSTRIPS.[4] Note that the builders of ABSTRIPS provide it with an abstraction hierarchy which is used to assign criticality values.

The following parts of the learner need to be designed and implemented:

- Using problem-solving traces to generate candidate abstraction spaces.
- Maintaining a partial order of abstraction spaces instead of generating total orders.
- Evaluating the achievability of plans produced in an abstraction spaces.

6 Planning with Abstraction Spaces

As Korf[14] describes, planning using abstraction requires mapping the initial problem to the highest abstraction level, planning in that abstract space, and then mapping the abstract plan to successive abstraction levels and expanding the plan until the ground space is reached. The PRODIGY problem solver will be extended to use the abstraction hierarchies described in the previous sections. The next section describes how the given problem is mapped into the abstract space as well as how the abstraction hierarchy is chosen to provide the most effective abstraction for a given problem. The following section describes the planning at the abstract level and how the abstract plan is refined to the more concrete levels. The last section describes the implementation's status.

6.1 Selecting an Abstraction Hierarchy

Section 5 described the techniques for producing a partial order of abstraction spaces. Before planning begins, one of the possible abstraction hierarchies (i.e., a total ordering on abstraction spaces) must be chosen. As described in section 4, the choice of an actual hierarchy is based on each goal state that the system is asked to solve.

The choice of an abstraction hierarchy for solving a particular goal state is limited by the abstractness of the goal state. Therefore, before the abstraction hierarchy is chosen for a problem the system attempts to transform the goal state into the most abstract one possible. The original

[4]To actually produce a finer grained abstraction hierarchy requires the additional piece of knowledge that if the robot is next to a door, then it must be in a room next to that door. However, even without this information the system can produce a useful abstraction hierarchy for this domain.

goal state can be transformed into a more abstract one by first removing any unnecessary details and then transforming atomic formulas into more abstract atomic formulas.

To remove details from the goal states require showing that certain atomic formulas in the goals are details. An atomic formula is a detail if it can be ignored at an abstract level and then considered at a lower abstraction space without generating an interaction. Consider the following example:

```
(and (next-to robot door5)
     (in-room robot room1))
```

Examining the preconditions of the operator for achieving `(next-to robot door5)`, the system can determine that if it achieves the second goal, `(in-room robot room1)`, and `door5` is a door of `room1` then it can achieve the first goal from the resulting state without clobbering the second goal. (The system uses the initial state to determine the relationship between `door5` and `room1`.) Therefore, the system can safely remove the `next-to` predicate from this particular problem at an abstract level and solve the goal: `(in-room robot room1)`.

Now, consider the situation where `door5` is not a door of `room1`. In this case the goal state is unachievable since the robot would have to be in two places at the same time and removing the `next-to` predicate will only delay the realization of this fact. The system will not abstract the goal because there is no way to easily achieve `next-to` once the `in-room` goal is achieved.

The next step is to transform detailed goal states into more abstract ones. The system does this using a set of predefined relations on the predicates. In the above example `(next-to robot door5)` could be replaced by `(or (in-room robot room3)(in-room robot room4))`. The danger of this approach is the new goal state may be harder to achieve than the original. To avoid making the problems harder, the transformations are limited to cases where an atomic formula can be replaced by a more abstract atomic formula. In this case no replacement would be made.

Once the system has simplified and abstracted the goal state, it chooses an abstraction hierarchy that will avoid interactions across abstraction levels. The system examines each of the preconditions of the operators that achieve the abstracted goals. If there are any preconditions that occur higher in the partial order, the group containing the goal predicate must be merged with the other group in the partial order. For example, consider the following goal state:

```
(and (next-to object2 door5)
     (closed door1))
```

If there is no way to abstract this goal state further, the system collapses the partial order as shown in Figure 8. The diagram on the left shows the partial order for the domain and the diagram on the right shows the collapsed partial order for the goal state. The program combines the `DoorStatus` group with the `RobotInRoom` group since the top-level goal of closing door1 will require getting the robot to a room next to the door. Similarly, the program combines `ObjectLocation` with `ObjectInRoom` because moving `object2` next to `door5` require that the object is in a room adjacent to `door5`.

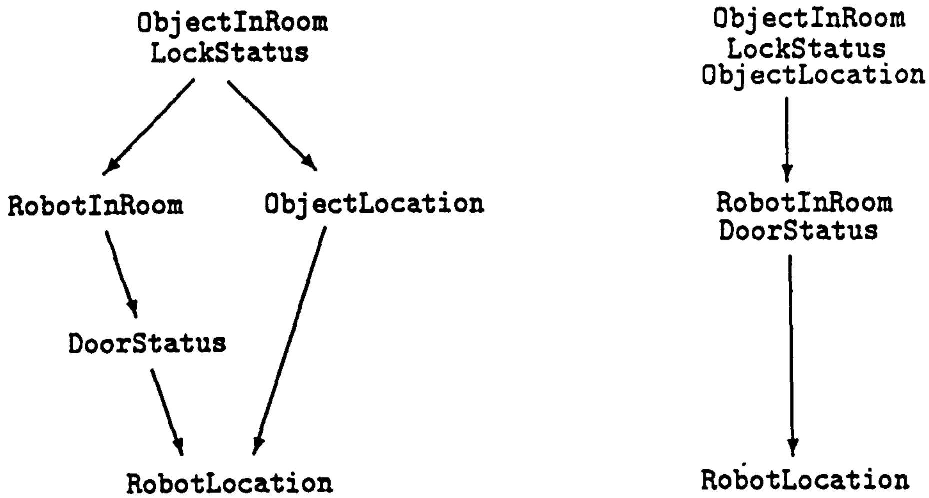

Figure 8: Selecting an Abstraction Hierarchy

6.2 Planning with an Abstraction Hierarchy

Once the system abstracts the goal state and chooses an appropriate abstraction hierarchy, it can attempt to solve the problem. First, the system loads the operators appropriate for the chosen level of abstraction. This is straightforward since each abstraction level is defined by the predicates used in that level. Determining the abstract operators is complicated slightly when two operators are indistinguishable at an abstract level. The system maintains a table which contains the mapping of abstract operators to the possible instantiations of these operators. Included in this table is a pointer to the place in the abstraction hierarchy where the abstract operator should be replaced by one of the more detailed operators. Thus, when the system loads a domain the appropriate abstract operators replace more detailed operators as necessary.

The implementation of the planning mechanism fits naturally into the PRODIGY framework[18, 19,20]. Planning at the most abstract level, PRODIGY simply constructs a plan using the abstract operators. If it fails, tnen there is no solution to the problem and the planner is finished. If it is successful, then an abstract solution to the problem is produced. The abstract plan is then refined using the same search tree to set up a number of subproblems, each of which corresponds to an operator application in the original tree, but has additional preconditions to satisfy. The effect of the noninteraction property is that each operator application in the abstract plan can be treated as a separate problem, thus considerably reducing the potential search space. The abstract planning mechanism gives each of the subproblems to PRODIGY to solve and then adds additional links to form a complete plan at each abstraction level. The refinement process continues until the solution is refined down to the ground space. If PRODIGY fails in the process of refining an abstraction level, the system first backtracks within the current level, and failing that, it may backtrack across levels of abstraction to find a different plan. Since the system keeps the problem-solving trees at each level of abstraction and links them up appropriately, the system can backtrack efficiently.

Abstract operators that can be specialized with several different operators make the refinement process slightly more complex. Each abstraction level is mapped to the next abstraction level via the operators, so every operator at one abstraction level will have one or more corresponding operators at the more detailed levels. In the simpler case the operator applications are refined by rematching the preconditions of the operator with the more detailed version of the operator and inserting additional operators to achieve the unmatched preconditions. In the case where an abstract operator application can be refined by several more detailed operators, the system chooses one, and if it results in failure it backtracks and considers the other choices.

Similarly, to exploit objects that are indistinguishable at an abstract level requires some additional work. One possible approach to using abstract objects is to treat them as an unlimited resource at an abstract level and then instantiate the abstract object with specific objects when the appropriate level has been reached. Another possibility is to replace each of the objects with abstract templates at the level in which they are indistinguishable and then replace them by particular objects at the level in which the objects are distinguishable.

6.3 Implementation Status

I have extended the PRODIGY system to plan using abstraction hierarchies and ran it both with and without the abstraction hierarchies produced for the ABSTRIPS domain. Because PRODIGY has a rich control language and uses a default depth-first search strategy, simple problems can be solved with little or no backtracking. In these cases, the overhead of expanding each abstraction level actually makes the use of abstraction more expensive. However, for more difficult problems which usually involve goal interactions, planning using the abstraction spaces produces performance improvements of an order of magnitude or more. The usefulness of planning using abstraction comes from focusing the planner on the difficult parts of the problem which often involve backtracking.

The following parts of the planner need to be designed and implemented:

- Simplifying a goal state and mapping it into a more abstract one.
- Selecting a particular abstraction hierarchy to be used for solving a problem or class of problems.
- Extending the abstraction refinement mechanism to handle an abstract operator that could be refined by several more specific operators.
- Developing and integrating techniques for handling objects as resources when they are indistinguishable at an abstract level.

7 The Utility of Hierarchical Planning

The usefulness of abstraction in planning increases with the complexity of the domains and problems to be solved. The performance improvement on a particular problem is the cost of solving the problem without abstraction compared to the cost of solving the problem with abstraction. The cost of using abstraction includes creating the partial order of abstraction spaces, selecting an abstraction hierarchy for a particular problem and the overhead of planning with the abstraction hierarchy. Each of these components are considered separately below.

The process of creating the partial order as described in Section 5 involves a number of steps, but it only needs to be done once for a given domain. Problem-solving traces are used to guide the creation of the partial order and avoid a brute-force search. Since it is assumed that a particular domain will be used to solve a large number of problems, then the cost of this step distributed over all of the problems is negligible.

Selecting an abstraction hierarchy for planning is a straightforward process that requires little search. However, since each problem is first mapped into a more abstract problem and then an abstraction hierarchy is chosen for that problem, the cost of this step is added to the cost of solving the problem. Should this step turn out to have a high cost, the selection of an abstraction hierarchy can be done by caching the abstraction hierarchies according to the combinations of goals the abstractions can be used to solve.

Using the abstraction hierarchies for planning is the most costly component. Initial experiments show that the overhead of using the abstractions (in an inefficient implementation) roughly doubles the problem-solving time in the worst case. This occurs on problems that can be solved easily and require little or no search. In contrast, on difficult problems the use of abstraction can improve performance by an order of magnitude or more. Thus, the overall utility of abstraction in a domain depends on the complexity of the domain and the difficulty of the problems to be solved.

In the thesis, the performance on a number of different domains will be measured, both with and without using abstraction. The domains will include the original STRIPS domain, the extended robot planning domain (Appendix B), the machine-shop scheduling domain (Appendix A), as well as one other additional domain. A large set of pseudo-randomly generated problems will be used to test each domain.

8 Related Work

This section describes related work on creating and using abstraction spaces for hierarchical planning. There is additional work on abstraction that is not described and includes research on characterizing the different types of abstractions[4,5,26], the utility of abstraction for problem solving[17,22], the use of skeletal plans to guide planning[10], creating aggregate objects to reduce search[2], removing irrelevant details through reformulation[28], as well as using abstractions for hierarchical planning[29,30,34,35].

The related work is broken up into two categories below: systems that use abstraction, and theories or models of abstraction. For each of the implemented systems, listed in chronological order, the following questions are answered: Does the system actually perform hierarchical planning in the sense of creating an abstract plan and then refining that plan at progressively more detailed levels? If not, how does the system use the abstractions? Do the abstractions produce plans that are noninteracting and achievable? Are the abstractions given to the system or are they generated?

8.1 Abstraction Planners

This section describes the systems that either perform hierarchical planning or use abstraction in a closely related way.

8.1.1 GPS

GPS[21], in addition to being one of the first planners, is also one of the earliest systems that used hierarchical planning. GPS is a means-ends analysis problem solver. Problems are cast in terms of an initial state, a goal state, and a set of operators that transform one state into another. The system is given an ordered set of differences that characterize the important features of the problem domain and a table of connections that specify which operators can be used to achieve which differences. GPS solves problems by reducing the differences between the current state and the goal state.

In Planning GPS, Newell and Simon explore hierarchical planning in the domain of logic. They create an abstraction of the domain by ignoring the logical connectives in the formulas. They form such an abstraction by only considering in the abstract space, what are called, the essential differences. Since the differences are completely ordered by difficulty, this consists of dividing the set of differences into two groups and removing the inessential, or easier, ones. The differences, difference orderings, and the point at which the differences are divided are provided by the implementors. The specialization of an abstract plan never introduces a new essential difference because the particular operators that achieve the inessential differences do not introduce them. Thus, the abstract plans in this domain are all noninteracting.

The system does not have a mechanism for avoiding achievability problems, and they arise frequently in this domain. As the authors point out, the number of spurious (unachievable) solutions generated in the abstract space determines the usefulness of the abstraction.

In addition to the work on abstraction in Planning GPS, there is also work on automatically ordering differences for GPS[6,7,8,11]. GPS solves problems by reducing the differences between the start state and the goal state. By analyzing the interactions of the operators that reduced these differences, the differences can be ordered such that once certain differences are eliminated they cannot be reintroduced. The criterion for ordering the differences is to minimize the interactions of the adds and deletes of the operators. This type of interaction also needs to be avoided across abstraction spaces in order to ensure the noninteraction property. Thus, the techniques used to produce the constraints on abstraction space orderings (as described in Section 5.1) are based on these difference ordering techniques.

8.1.2 ABSTRIPS

ABSTRIPS[24] assigns criticalities, numbers indicating the relative difficulty, to the preconditions of each operator and then uses these criticalities to plan abstractly. The system first creates a skeletal plan which satisfies only the preconditions of the operators from the highest level of criticality. The system then refines the operators in the skeletal plan by adding the preconditions at the next level of criticality and inserting steps into the plan to achieve these preconditions. ABSTRIPS repeats this process until the plan is expanded to the lowest level of criticality.

ABSTRIPS is given an initial abstraction hierarchy which is then used to automatically assign the criticalities as follows. First, literals whose truth values cannot be changed by an operator are placed in the highest abstraction space. Next, predicates that cannot be achieved with a "short" plan are placed in the next highest abstraction space. The remaining predicates are placed in a lower level corresponding to their place in the abstraction hierarchy. The essence of the approach is the short plan heuristic which separates the details from the important information. The system essentially produces a three-level abstraction hierarchy, with the static predicates first, the "important" predicates second, and the details third. Any further refinement of levels comes from the user-defined abstraction hierarchy.

The noninteraction property holds for all the plans produced in the ABSTRIPS domain for two reasons. First, the system lumps all the difficult predicates into one abstraction level. For this domain, this guaranteed that no interaction would occur between this level and any below it. (The static level cannot cause an interaction problem because those predicates cannot change.) Second, the noninteraction property between detailed levels depends on the "right" hierarchy being given to the system, and for this particular domain, the "right" hierarchy was given. In [13], I describe a completely automated algorithm for producing abstraction spaces which when given the ABSTRIPS domain generates abstraction spaces equivalent to the ones ABSTRIPS used.

Because of the simplicity of the domain considered in ABSTRIPS, achievability problems do not arise.

8.1.3 NOAH

NOAH[25] is a nonlinear planner and so it creates a partial plan instead of a linear plan, making planning commitments only where necessary. The operators in NOAH, which are completely defined by the user, can be expanded to different levels of detail during planning. The ability to jump around the planning space and ignore some preconditions of operators and work on others was claimed to be another technique for performing hierarchical planning. However, NOAH is not actually planning at different levels of abstraction in the sense of creating an abstract plan and then refining that plan. The problem with NOAH's approach to abstraction is that it may expand one part of the plan down to a given level and then work on a different part of the plan at a different level. A so called abstract plan could be produced and then become invalid when another part of the plan is expanded.

The problem of the abstract plan becoming invalid is caused by an interaction across abstraction levels. Thus, NOAH uses abstract plans that do not have the noninteraction property. To handle this problem a *hierarchical kernel* is defined for each node in the search, which states the conditions that were tested in order to apply the operator at that node. Then, before any node is expanded further, the hierarchical kernel for that node is tested to see if the appropriate conditions still hold. In the case where the hierarchical kernel does not hold, then NOAH has to reachieve the missing conditions or backtrack to the point it undid one or more of these conditions. In general, reachieving the deleted conditions or finding another way to solve the problem that does not violate the conditions can be a difficult problem and is not fully addressed in NOAH.

Achievability problems rarely arise in NOAH due to the combination of the nonlinear planning and the fact that the particular domains considered never require the planner to make arbitrary commitments. However, in a more complex domain achievability problems could arise.

Wilkins[35] identified another problem with NOAH's approach to abstraction that is particular to nonlinear planning. The problem is that since the planner is in effect jumping around the search space, it may expand one part of the plan to too detailed a level before another part of the plan is expanded at all. The result is that state inconsistencies can arise. If in one part of the plan the system decides to move a robot from one room to another, but an earlier part of the plan which has not been expanded yet may also require moving the robot. Since the earlier part of the plan has not been expanded to the level of detail before the later part of the plan, the planner may be moving the robot from the wrong room. Wilkins proposes several solutions to this problem, but they all require noticing where these situations can arise and annotating the operators in order to prevent the expansion at too detailed a level before earlier parts of the plan have been extended to that level.

8.1.4 MOLGEN

MOLGEN[27] is a system for planning experiments in the domain of molecular genetics. The system plans abstractly using both a given hierarchy of operators and objects, however, the planning is similar to NOAH's planning in that the system can introduce operators and objects from any level in the abstraction hierarchy at anytime. The noninteraction problem is not explicitly dealt with in MOLGEN, and the problem of an abstract plan becoming invalid does not seem to arise in this domain.

In contrast, MOLGEN does use a constraint mechanism to handle subproblems that are not independent. Stefik argues that an abstract plan can rarely be decomposed into independent subproblems, but they can be divided into nearly independent ones. His solution to this problem is to use constraints, letting decisions made in the solution of one subproblem constrain the possible solutions for another subproblem. Note, however, that the achievability problem is not completely solved since subproblems may still arise which are unsolvable.

8.1.5 SOAR

Unruh[32,33] proposes to implement abstraction as a weak method in SOAR[15], which is a general architecture for problem solving based on the use of problem spaces. SOAR has a set of built-in weak methods and a new method, abstraction, is currently being implemented. If SOAR is working on a goal and reaches an impasse, a point in the search where it does not know how to proceed, then it subgoals on a new problem space to resolve the impasse. One technique frequently used in SOAR is to perform look-ahead search to determine how to proceed. This can be quite expensive and an alternative is to perform such look-ahead searches in an abstract space. The system creates abstractions through experimentation and since the abstraction is done at run-time the abstractions can be chosen based on the particular subgoal being solved. Even though the system only uses the abstractions as control heuristics, the noninteraction and achievability properties are still important if the abstractions are going to provide useful control information.

8.1.6 PLANEREUS

Anderson[1] proposes a technique for automatically generating abstract operators. Given a strips-like domain with operators for performing similar operations on different objects, the system constructs both hierarchies of objects and hierarchies of abstract operators. These hierarchies are constructed by examining the operators that share common effects and adding new abstract operators that contain only the shared preconditions. The generalization process also creates the object hierarchies by adding a new abstract object type when two operators perform the same operations on different objects. These abstraction hierarchies are then used to construct abstract macros by generalizing a particular plan as far as possible without loosing the dependency structure of the plan. These macros are then added to the operator hierarchy as new abstract operators which can be used to solve analogous problems in the future.

The creation of abstract operators is similar to the formation of abstract operators from operators that are indistinguishable at an abstract level. However, the process of forming the abstract operators and the way the abstract operators are used is quite different. In this proposal, an abstract operator cannot be formed unless the differences between the operators can be shown to be details. In Anderson's work all possible abstract operators are formed simply by dropping the differences without regard to the difficulty of achieving those differences. He does not address the problem of specializing an abstract plan when an achievability problem arises. On the other hand, by storing the abstract macros in the hierarchy, if there is a macro for solving a particular problem then there will not be any problems with interactions between abstraction levels. However, the problem of dealing with potentially large numbers of abstract macros is not fully addressed.

8.2 Models of Abstraction

This sections describe work that deals with different theories or models of abstraction.

8.2.1 Plan Synthesis

Rosenschein[23] casts planning into propositional dynamic logic and then uses this framework to analyze hierarchical planning. He argues that single-level planning can be extended to hierarchical planning simply by viewing each action at level k as a problem to be solved at level k+1, where the constraints on the actions at level k become constraints on the plan at level k+1. Thus, the final plan must obey the constraints that arise at each of the abstract levels. Viewing the abstract constraints on actions as constraints on plans at the next level is equivalent to the noninteraction property.

Rosenschein analyzes hierarchical planning in NOAH within this framework and points out that NOAH violates the above constraint. Thus, seemingly correct plans at one level can be expanded into incorrect plans at lower levels. He argues that this undermines the rationale for hierarchical planning of reducing complexity through factorization since "unexpected global interactions" can arise.

8.2.2 Hobbs' Granularity Theory

Hobbs presents a theory of granularity[12] that allows one to view the world at different grain-sizes. He argues that the ability to switch between granularities is a fundamental ability of humans. Depending on the context, the relevant properties of several objects may be indistinguishable. This allows us to focus on the important properties by viewing the world at different grain-sizes. To switch between different granularities requires a complex set of articulation axioms which specify the precise relationships.

The work in this proposal implements a small part of this theory, although the learned abstractions are much more limited than the ones Hobbs' envisions in his theory. Depending upon the particular problems to be solved certain classes of predicates can be ignored. The result of ignoring these predicates is that some objects and operators in the world become indistinguishable which in turn can be used to simplify planning. Given a different class of problems, different predicates would be relevant and perhaps a different abstraction would be appropriate.

8.2.3 Korf's Model of Abstraction

Korf[14] characterizes abstraction as one of several possible knowledge sources. He shows that a single level of abstraction can reduce the total search time from $O(n)$ to $O(\sqrt{n})$, and multiple levels of abstraction can reduce the search time from $O(n)$ to $O(logn)$, where n is the number of states and the time is proportional to the number of states searched. These results are based on an average case analysis that assumes the distribution remains constant over different levels of abstraction and the number and ratio of the sizes of the abstraction spaces are optimal. Although these are rather strong assumptions, Korf provides a useful analysis of the potential utility of abstraction.

As Tenenberg[31] points out, Korf's analysis assumes that the mapping between an abstract plan and a specialization of the abstract plan is trivially known and a specialization always exists. However, a hierarchical planner may expend a great deal of work searching for an appropriate mapping and in some cases no corresponding specialization exists. Consider the route planning domain that Korf describes in [14]. The problem is to plan a route between any two points where the operators move between adjacent intersections. By building up a set of macro operators he creates abstract operators that move between more distant points. Planning involves mapping the original problem into an abstract problem and then finding a route between the points in the abstract space. Once this abstract solution is found, the solution is found! Each macro operator is composed of the individual operators that achieve the macro so there is no additional work to map an abstract solution into a detailed solution. Of course, this assumes that the initial state is fixed.

Korf models an abstraction by viewing the states of an abstract space as a subset of the states in the base space. The operators of the abstract space transform states in the abstract space to other states in the abstract space. The work described here can be viewed similarly. Given an initial domain axiomatization in terms of the primitive operators, the operators are used to create abstract operators that map between abstract states. The process of creating the abstract operators is performed by determining how the states can be abstracted relative to the operators. The operators are abstracted by dropping preconditions and effects that correspond to the predicates being abstracted from the state. Korf does not include in his analysis the additional search reduction possible by combining indistinguishable operators and objects into abstract units.

8.2.4 Tenenberg's Reduced Models and Analogy

Tenenberg considers both abstraction using reduced models and abstraction using analogy in his thesis[31]. He presents a careful formalization of both STRIPS and ABSTRIPS and argues that simply dropping preconditions in ABSTRIPS has serious problems since it can lead to inconsistent states. Instead he creates reduced models of a planning domain by partitioning the predicates into classes based on a static theory of a domain. In his formalization he shows that the resulting models have the upward-solution property, which states that if a solution exists in the original model, there are corresponding solutions in the reduced models. His work does not address if and how an abstract solution can be refined into a detailed solution.

His work on abstraction using analogy extends the use of type hierarchies to a planning system. Given the abstraction hierarchies for both the objects and operators of a planning domain, they can be used to plan abstractly. Objects and operators used for analogous purposes can be mapped into abstract objects and operators. The resulting abstract plans can then be saved as macro operators which can be used to solve analogous problems.

The work described in this proposal integrates parts of these two different approaches into a single framework. Abstraction using reduced models is used to simplify the planning domain. Then the resulting domain may have operators and objects that are indistinguishable at an abstract level and can thus be treated as such. In contrast to Tenenberg's work, the issue of refining abstract solutions is addressed here with the noninteraction and achievability properties.

9 Research Plan

This section describes a set of milestones to complete the thesis and presents a timetable showing when I expect to achieve them.

9.1 Milestones

Theory: Refine the definitions of the properties in Section 2. This includes stating the properties more rigorously as well as determining the scope of the abstractions that can be generated using the techniques described in this thesis proposal.

Learning: Work out the details and implement the algorithms for creating a partial order of abstraction spaces for a domain (Section 5). This includes using example traces to generate candidate abstraction spaces and then evaluating the plans produced in these abstraction spaces for noninteraction and achievability.

Planning: Design and implement the algorithms for selecting a particular abstraction hierarchy for abstract planning and the extensions to PRODIGY for refining abstract plans into more detailed plans (Section 6). The extensions includes handling abstract operators that can be specialized by several different operators as well as utilizing classes of abstract objects which will need to be mapped into more detailed classes of objects as a plan is refined.

Analysis: Test and evaluate the techniques on at least four planning domains including the original STRIPS domain[9], an augmented STRIPS domain[18] (described in Appendix B) and a machine-shop scheduling domain[18] (described in Appendix A). Other possible domains include a telescope building domain[3], the R1 Vax configuration domain[16], and a warehouse operations domain.

A realistic timetable for achieving the milestones is shown in Figure 9.

9.2 Issues Not Addressed

The following issues will not be addressed in this thesis:

- There are certainly abstractions at a more fine-grained level than the state space. However, it is not clear how to find them, represent them or use them. Therefore, the abstractions in this thesis will be limited to abstracting the domain by completely removing certain classes of predicates, abstracting goal states by removing details and mapping goals into more abstract goals, abstracting operators by removing details and combining them when they are indistinguishable at an abstract level, and abstracting objects by removing details and grouping then into classes.

- In some cases the system will need a more complete axiomatization of the domain in order to prove that certain abstraction spaces always produce noninteracting plans and for mapping goal states into more abstract ones. To acquire this additional information, I assume that the system has access to a domain expert that can be queried for domain knowledge.

10 Contributions

Most of the planning domains explored to date are quite simple. To a large extent this is due to the large search spaces that are only compounded by adding more details to the problems. This proposal presents an automatic approach to separating out the details of a domain from the hard problems, thus allowing more interesting problems to be addressed without paying a high cost for the additional details.

The theory and implementation will be tested in the context of the PRODIGY problem solver. However, the basic ideas in the thesis are applicable to any operator-based problem solver.

The major contributions of this thesis are as follows:

1. The identification of the critical properties of abstract plans. These are the noninteraction and achievability properties, which provide a metric for evaluating abstraction spaces used for hierarchical planning. The previous work on hierarchical planning can be better understood in the context of these well-defined properties.

2. The dynamic selection of an abstraction hierarchy. Instead of simply precomputing and using a single abstraction hierarchy, the system can create a partial order of abstraction spaces

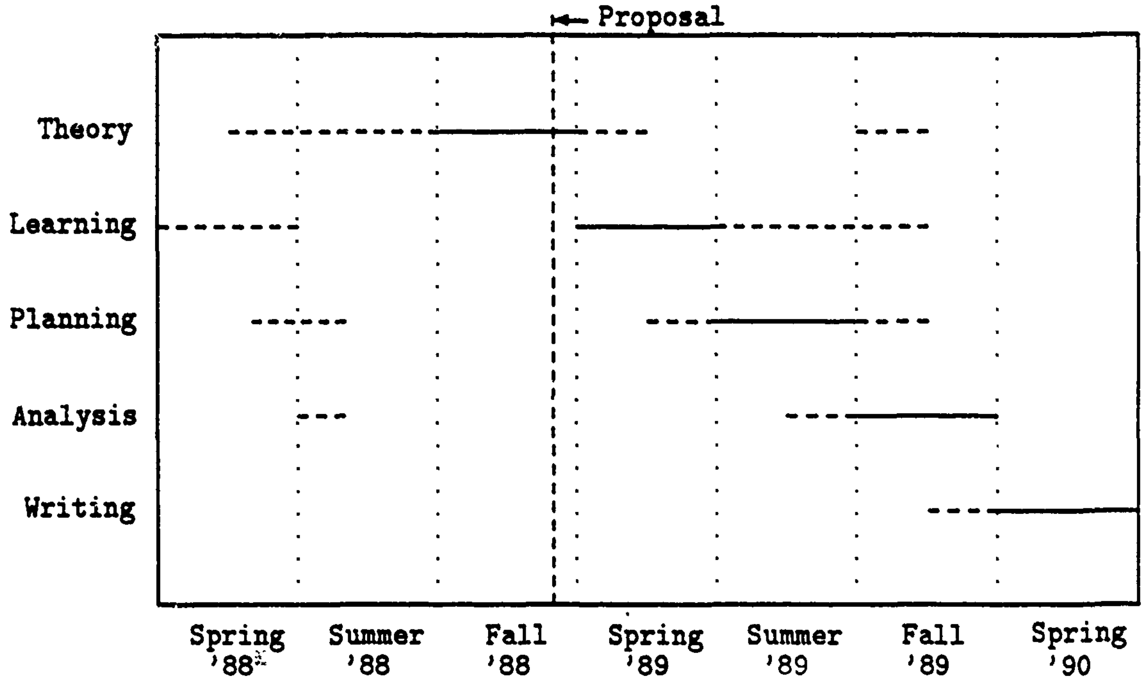

Figure 9: Realistic Timetable

and then dynamically select a particular abstraction hierarchy based on the problem or class of problems to be solved. This allows the maximum benefit to be gained from the possible abstractions in a domain.

3. The formation of operator and object hierarchies through state-space abstraction. Representing abstractions by simplifying the state space allows the system to identify operators and objects that are indistinguishable at some abstract level and hence exploit these abstractions during planning. Indistinguishable operators are treated as a single abstract operator and indistinguishable objects are treated as a limited resource instead of individual objects.

4. The techniques for learning abstraction spaces. A partial order of possible abstraction spaces is learned by using problem-solving traces to generate possible abstraction spaces and then testing that the plans produced in these spaces will be noninteracting and achievable. The partial order is then used to select an abstraction hierarchy that is tailored to solve a particular problem.

5. The extension of the techniques for planning with abstraction spaces. Instead of simply attempting to solve a problem in an abstract space, a goal state is simplified, mapped to a more

abstract goal state, and then an appropriate abstraction hierarchy is chosen. The refinement of abstract plans uses operator and object hierarchies that depend on the problem to be solved. And if planning failures arise, the system can backtrack efficiently across abstraction levels.

6. An analysis of the effectiveness of the techniques. The performance on a number of different domains will be measured both with and without the learned abstractions.

11 Acknowledgements

I would like to thank my advisor, Jaime Carbonell, for his guidance and insights on this work. I would also like to thank Oren Etzioni, Steve Minton, and Josh Tenenberg for many helpful discussions, suggestions and ideas related to abstraction. Finally, I would like to thank Claire Bono, Richard Cohn, Oren Etzioni, Yolanda Gil, Robert Joseph, Dan Kuokka, Steve Minton, Alicia Perez, Santiago Rementeria, Manuela Veloso, and the members of my committee, Jaime Carbonell, Tom Mitchell, Paul Rosenbloom, and Herb Simon, for their comments on various drafts of the proposal.

A Machine Shop Scheduling Domain

This section describes a machine shop scheduling domain and the corresponding abstraction spaces that the approach described in the proposal would produce. The operators for this domain are shown at the end of this appendix. In this domain there are a number of possible operations that can be performed on a given set of parts. In order to create a schedule, constraints about the order of operations as well as resource limitations must be taken into account. The final schedule specifies which operators can be performed on which parts in parallel. The basic operations that can be performed on an object are changing the shape, making a hole, painting, changing the surface condition, forming a compound object and changing the temperature. Each basic operation may have one or more operators for performing those operations (e.g., an object can be painted using a spray painter or an immersion painter).

A partial order of abstraction spaces for this domain is shown in Figure 10. This partial order is roughly what would be produced by the abstraction generation part of the system. The predicates related to placing the operations in a schedule are placed at the bottom of the partial order. Immediately above those are the predicates related to whether the parts can be clamped to a machine and whether the parts are at an acceptable temperature to perform the operation. The remaining five sets of predicates are all related to properties that can be given as top-level goals. Notice that these are also ordered by the constraints on the order in which these operators must be performed (i.e., changing the shape of an object must be done before it is painted).

Using abstraction spaces in this domain will be highly effective in reducing search. The reasons for the improved performance in this domain are as follows: First, the operators are highly interrelated through the effects of the operators, but there are not many dependencies among operators (i.e., one operator that depends on another to achieve it). Therefore, the partial order for the

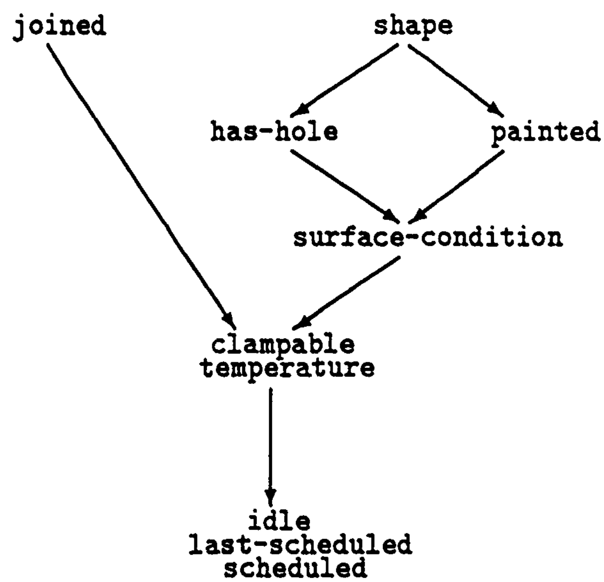

Figure 10: Partial Order of Abstraction Spaces

domain can be use to solve any goal state without collapsing it. Second, the ordering among shape, has-hole, painted, and surface-condition in the abstraction hierarchy ensures that these operators are performed in the correct order. Third, there are several different possible operators for achieving each of the possible goals and the hierarchy allows these operators to be combined into abstract operators. Thus, at an abstract level, the number of operators is roughly halved. Fourth, since all of the predicates involved with placing the operators in a schedule are at the bottom of the hierarchy, the system can first create an abstract plan that only deals with ordering the operators to be performed on a particular object and then, when the plan is refined, place these operators in a schedule.

The operators for the scheduling domain are as follows:

```
(POLISH
  (preconds
    (and
      (is-object <obj>)
      (temperature <obj> COLD)
      (clampable <obj> POLISHER)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle POLISHER <time>)))
  (effects (
    (del (surface-condition <obj> <*7>))
    (add (surface-condition <obj> POLISHED))
    (del (last-scheduled <obj> <prev-time>))
    (add (last-scheduled <obj> <time>))
    (add (scheduled <obj> POLISHER <time>)))))

(COOL
  (preconds
    (and
      (is-object <obj>)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (temperature <obj> HOT)))
  (effects (
      (del (temperature <obj> HOT))
      (del (last-scheduled <obj> <prev-time>))
      (add (temperature <obj> COLD))
      (add (last-scheduled <obj> <time>))
      (add (schedule <obj> COOL <time>)))))

(ROLL
  (preconds
    (and
      (is-object <obj>)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle ROLLER <time>)))
  (effects (
     (del (shape <obj> <old-shape>))
     (del (temperature <obj> <old-temp>))
     (del (last-scheduled <obj> <prev-time>))
     (del (surface-condition <obj> <*1>))
     (del (painted <obj> <*2>))
     (del (has-hole <obj> <*3> <*4>>))
     (add (temperature <obj> HOT))
     (add (shape <obj> CYLINDRICAL))
     (add (last-scheduled <obj> <time>))
     (add (scheduled <obj> ROLLER <time>)))))

(LATHE
  (preconds
    (and
      (is-object <obj>)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle LATHE <time>)))
  (effects (
     (del (shape <obj> <shape>))
     (del (surface-condition <obj> <*3>))
     (del (painted <obj> <*4>))
     (del (last-scheduled <obj> <prev-time>))
     (add (surface-condition <obj> ROUGH))
     (add (shape <obj> CYLINDRICAL))
     (add (last-scheduled <obj> <time>))
     (add (scheduled <obj> LATHE <time>)))))

(GRIND
  (preconds
    (and
      (is-object <obj>)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle GRINDER <time>)))
  (effects (
     (del (surface-condition <obj> <*1>))
     (add (surface-condition <obj> SMOOTH))
     (del (painted <obj> <*2>))
     (del (last-scheduled <obj> <prev-time>))
     (add (last-scheduled <obj> <time>))
     (add (scheduled <obj> GRINDER <time>)))))

(PUNCH
  (preconds
    (and
      (is-object <obj>)
      (is-punchable <obj> <hole-width> <orientation>)
      (temperature <obj> COLD)
      (clampable <obj> PUNCH)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle PUNCH <time>)))
  (effects (
    (add (has-hole <obj> <hole-width> <orientation>))
    (del (surface-condition <obj> <*33>))
    (add (surface-condition <obj> ROUGH))
    (del (last-scheduled <obj> <prev-time>))
    (add (last-scheduled <obj> <time>))
    (add (scheduled <obj> PUNCH <time>)))))
```

```
(DRILL-PRESS
  (preconds
    (and
      (is-object <obj>)
      (is-drillable <obj> <orientation>)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle DRILL-PRESS <time>)
      (have-bit <hole-width>)))
  (effects (
    (add (has-hole <obj> <hole-width> <orientation>))
    (del (last-scheduled <obj> <prev-time>))
    (add (last-scheduled <obj> <time>))
    (add (scheduled <obj> DRILL-PRESS <time>)))))

(BOLT
  (preconds
    (and
      (is-object <obj1>)
      (is-object <obj2>)
      (can-be-bolted <obj1> <obj2> <orientation>)
      (is-bolt <bolt>)
      (is-width <width> <bolt>)
      (has-hole <obj1> <width> <orientation>)
      (has-hole <obj2> <width> <orientation>)
      (last-scheduled <obj1> <prev-time1>)
      (last-scheduled <obj2> <prev-time2>)
      (later <time> <prev-time1>)
      (later <time> <prev-time2>)
      (idle BOLTING-MACHINE <time>)
      (composite-object <new-obj> <orientation>
                        <obj1> <obj2>)))
  (effects (
     (del (last-scheduled <obj1> <prev-time1>))
     (del (last-scheduled <obj2> <prev-time2>))
     (add (last-scheduled <new-obj> <time>))
     (add (is-object <new-obj>))
     (del (is-object <obj1>))
     (del (is-object <obj2>))
     (add (joined <obj1> <obj2> <orientation>))
     (add (scheduled <new-obj> BOLTING-MACHINE
                     <time>)))))

(WELD
  (preconds
    (and
      (is-object <obj1>)
      (is-object <obj2>)
      (can-be-welded <obj1> <obj2> <orientation>)
      (last-scheduled <obj1> <prev-time1>)
      (last-scheduled <obj2> <prev-time2>)
      (later <time> <prev-time1>)
      (later <time> <prev-time2>)
      (idle WELDER <time>)
      (composite-object <new-obj> <orientation>
                        <obj1> <obj2>)))
  (effects (
     (del (last-scheduled <obj1> <prev-time1>))
     (del (last-scheduled <obj2> <prev-time2>))
     (add (last-scheduled <new-obj> <time>))
     (del (temperature <new-obj> <old-temp*>))
     (add (temperature <new-obj> HOT))
     (add (is-object <new-obj>))
     (del (is-object <obj1>))
     (del (is-object <obj2>))
     (add (joined <obj1> <obj2> <orientation>))
     (add (scheduled <new-obj> WELDER <time>)))))

(SPRAY-PAINT
  (preconds
    (and
      (sprayable <paint>)
      (is-object <obj>)
      (shape <obj> <s>)
      (regular-shape <s>)
      (temperature <obj> COLD)
      (clampable <obj> SPRAY-PAINTER)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle SPRAY-PAINTER <time>)))
  (effects (
    (add (painted <obj> <paint>))
    (del (surface-condition <obj> <*2>))
    (del (last-scheduled <obj> <prev-time>))
    (add (last-scheduled <obj> <time>))
    (add (scheduled <obj> SPRAY-PAINTER <time>)))))

(IMMERSION-PAINT
  (preconds
    (and
      (is-object <obj>)
      (have-paint-for-immersion <paint>)
      (last-scheduled <obj> <prev-time>)
      (later <time> <prev-time>)
      (idle IMMERSION-PAINTER <time>)))
  (effects (
    (del (surface-condition <obj> POLISHED))
    (add (painted <obj> <paint>))
```

```
    (del (last-scheduled <obj> <prev-time>))
    (add (last-scheduled <obj> <time>))
    (add (scheduled <obj> IMMERSION-PAINTER
                    <time>)))))


(IS-CLAMPABLE
  (preconds
    (and
      (has-clamp <machine>)
      (temperature <obj1> COLD)))
  (effects ((add (clampable <obj1> <machine>)))))


(INFER-IDLE
  (preconds
    (forall (<obj2> <m>)
     (scheduled <obj2> <m> <time>)
     (not-equal <m> <mach>)))
  (effects (
    (add (idle <mach> <time>)))))
```

B Robot Planning Domain

```
(PICKUP-OBJ
 (preconds
   (and (arm-empty)
        (next-to robot <object>)
        (carriable <object>)))
 (effects
   ((del (arm-empty))
    (del (next-to <object> <object.a>))
    (del (next-to <object.b> <object>))
    (del (next-to <object> <door>))
    (del (next-to robot <object>))
    (add (holding <object>)))))


(PUTDOWN
 (preconds
   (holding <object>))
 (effects
   ((del (holding <object>))
    (add (next-to robot <object>))
    (add (arm-empty)))))


(PUTDOWN-NEXT-TO
 (preconds
   (and (holding <object>)
        (is-object <object.2>)
        (inroom <object.2> <room.object>)
        (inroom <object> <room.object>)
        (next-to robot <object.2>)))
 (effects
   ((del (holding <object>))
    (add (next-to <object> <object.2>))
    (add (next-to robot <object>))
    (add (next-to <object.2> <object>))
    (add (arm-empty)))))


(PUSH-TO-DR
 (preconds
   (and (is-door <door>)
        (dr-to-rm <door> <room>)
        (inroom <object> <room>)
        (next-to robot <object>)
        (pushable <object>)))
 (effects
   ((del (next-to robot <object.a>))
    (del (next-to <object> <object.b>))
    (del (next-to <object.c> <object>))
    (add (next-to <object> <door>))
    (add (next-to robot <object>)))))


(PUSH-THRU-DR
 (preconds
   (and (is-room <room.x>)
        (dr-to-rm <door> <room.x>)
        (is-door <door>)
        (opened <door>)
        (next-to <object> <door>)
        (next-to robot <object>)
        (pushable <object>)
        (connects <door> <room.x> <room.y>)
        (inroom <object> <room.y>)))
 (effects
   ((del (next-to robot <object.a>))
    (del (next-to <object> <object.b>))
    (del (next-to <object.c> <object>))
    (del (inroom robot <room.y>))
    (del (inroom <object> <room.y>))
    (add (inroom robot <room.x>))
    (add (inroom <object> <room.x>))
    (add (next-to robot <object>)))))


(GO-THRU-DR
 (preconds
   (and (arm-empty)
        (is-room <room.x>)
        (dr-to-rm <door> <room.x>)
        (is-door <door>)
        (opened <door>)
        (next-to robot <door>)
        (connects <door> <room.x> <room.y>)
        (inroom robot <room.y>)))
 (effects
   ((del (next-to robot <object>))
    (del (inroom robot <room.y>))
    (add (inroom robot <room.x>)))))


(CARRY-THRU-DR
 (preconds
   (and (is-room <room.x>)
        (dr-to-rm <door> <room.x>)
        (is-door <door>)
        (opened <door>)
        (is-object <object>)
        (holding <object>)
        (connects <door> <room.x> <room.y>)
        (inroom <object> <room.y>)
        (inroom robot <room.y>)
```

```
      (next-to robot <door>)))
 (effects
   ((del (next-to robot <object>))
    (del (inroom robot <room.y>))
    (del (inroom <object> <room.y>))
    (add (inroom robot <room.x>))
    (add (inroom <object> <room.x>)))))


(GOTO-DR
 (preconds
   (and (is-door <door>)
        (dr-to-rm <door> <room>)
        (inroom robot <room>)))
 (effects
   ((del (next-to robot <object>))
    (del (next-to robot <door>))
    (add (next-to robot <door>)))))


(PUSH-BOX
 (preconds
   (and (is-object <object.a>)
        (is-object <object.b>)
        (inroom <object.b> <room>)
        (inroom <object.a> <room>)
        (pushable <object.a>)
        (next-to robot <object.a>)))
 (effects
   ((del (next-to robot <object>))
    (del (next-to robot <door>))
    (del (next-to <object.a> <object.c>))
    (del (next-to <object.d> <object.a>))
    (del (next-to <object.a> <door>))
    (add (next-to robot <object.a>))
    (add (next-to robot <object.b>))
    (add (next-to <object.a> <object.b>))
    (add (next-to <object.b> <object.a>)))))


(GOTO-OBJ
 (preconds
   (and (is-object <object>)
        (inroom <object> <room>)
        (inroom robot <room>)))
 (effects
   ((add (next-to robot <object>))
    (del (next-to robot <door>))
    (del (next-to robot <object>)))))


(OPEN
 (preconds
   (and (is-door <door>)
        (unlocked <door>)
        (next-to robot <door>)
        (closed <door>)))
 (effects
   ((del (closed <door>))
    (add (opened <door>)))))


(CLOSE
 (preconds
   (and (is-door <door>)
        (next-to robot <door>)
        (opened <door>)))
 (effects
   ((del (opened <door>))
    (add (closed <door>)))))


(LOCK
 (preconds
   (and (is-door <door>)
        (is-key <door> <object>)
        (holding <object>)
        (dr-to-rm <door> <room>)
        (inroom <object> <room>)
        (next-to robot <door>)
        (closed <door>)
        (unlocked <door>)))
 (effects
   ((del (unlocked <door>))
    (add (locked <door>)))))


(UNLOCK
 (preconds
   (and (is-door <door>)
        (is-key <door> <object>)
        (holding <object>)
        (dr-to-rm <door> <room>)
        (inroom <object> <room>)
        (inroom robot <room>)
        (next-to robot <door>)
        (locked <door>)))
 (effects
   ((del (locked <door>))
    (add (unlocked <door>)))))
```

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CONCURRENCE FORM

The Geophysics Laboratory requests the continuation of the AFOSR fellowship for Mr. David J. Knudsen, studying Ionospheric Physics at Cornell University.

Give a brief statement of laboratory and/or Dr. Herbert Carlson's (fellow's mentor) involvement with Mr. David J. Knudsen.

Mr David Knudsen is one of two students pursuing a PhD thesis based on data collected during the AFGL Polar Arcs Rocket Campaign in Sondrestromfjord Greenland. He is making good progress.

for [signature] 12 Jun 89
Chief Scientist Date

[signature] 6/9/89
Mentor Date

S-789-000-038

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CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David J. Knudson

University: Cornell University   Subcontract: S-789-000-038

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   No courses were taken since I have completed all required course work

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Please see attached sheet

"I certify that all information stated is correct and complete."

David J Knudsen

Signature/Fellowship Recipient

David J Knudsen

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David J. Knudsen is making satisfactory academic progress toward a Ph.D. in the area of Ionospheric Physics in the discipline of Electrical Engineering for the Spring 1989 term."

Michael C. Kelley

Signature/Advising Professor

Professor M. C. Kelley

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4670C

17 May, 1989

2. Research and progress towards dissertation
David Knudsen
Spring Semester, 1989

My work this spring was concentrated on two main projects:

Alfven wave project - I spent a major portion of this semester writing a much more general version of the simulation that I presented at the American Geophysical Union Fall Conference in December 1988. The new version of model presented many added difficulties which consumed much of my time. The simulation solves for the electric and magnetic fields in two coupled low-frequency electromagnetic modes (the fast and slow Alfven modes) as they propagate from the magnetosphere and reflect off of both the ionosphere and the earth's surface. The model takes as input a detailed model of the ionosphere and lower atmosphere which was created using data from a rocket and the HILAT satellite. I am currently in the process of organizing the experimental and simulation results into a paper which will be submitted for publication later this year. A tentative title for the paper is "Comparison of Simulated and Measured Alfven Waves in the High Latitude Ionosphere".

Thesis Introduction - Since the main topic of my thesis is on the interaction of Alfven waves with the ionosphere, I spent several weeks this semester gathering references and outlining an introductory chapter on Alfven waves. In March I presented the information in two lectures to a graduate class on the topic of plasma waves.

In the summer months I will begin preparation of my thesis, and continue to work on publications. I anticipate that the writing process will lead to changes in data analysis and in the numerical simulation, so some of my time will be spent revising work on those projects.

CONCURRENCE FORM

The Geophysics Laboratory requests the continuation of the AFOSR fellowship for Mr. David J. Knudsen, studying Ionospheric Physics at Cornell University.

Give a brief statement of laboratory and/or Dr. Herbert Carlson's (fellow's mentor) involvement with Mr. David J. Knudsen.

AFGL involvement with Mr. David Knudsen has focused on the AFGL POLAR ARCS Rocket program analysis and interpretation. Principals in the interaction with Mr. Knudsen have been Ed Weber and Herb Carlson from AFGL and Mike Kelley from Cornell. The POLAR ARCS program continues to hold a high priority within AFGL, and Mr. Knudsen continues to be in a position to contribute materially. Our next major POLAR ARCS meeting is scheduled for 17-19 April 1989 and we look forward to Mr. Knudsen's results on the electrodynamics analysis as they pertain to the full global circuitry problem our program is addressing.

Richard S. Hendl, 6 FEB 89 — HCarlson 6 Feb 1989

Chief Scientist Date — Mentor Date

S-789-000-038

·· 29

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David J. Knudsen

University: Cornell University   Subcontract: S-789-000-038

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   none (course work is completed)

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   please see attached sheet

"I certify that all information stated is correct and complete."

David J Knudsen

Signature/Fellowship Recipient

David J. Knudsen

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. David J. Knudson is making satisfactory academic progress toward a Ph.D. in the area of Ionospheric Physics in the discipline of Electrical Engineering for the Fall 1988 term."

Michael C. Kelley

Signature/Advising Professor

M. C. Kelley

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4670C

17 January, 1989

2. Research and progress towards dissertation

David Knudsen

Fall Semester, 1989

A large part of my work during the fall semester was in preparation for the Fall Meeting of the American Geophysical Union in December. At that meeting I presented a poster talk describing results of a computer code that I wrote to simulate the interaction of low frequency Alfven waves (.01 - 10 Hz) with the high-latitude ionosphere. The simulation predicted height profiles of the amplitudes of the electric and magnetic fields associated with Alfven waves.

Alfven wave fields have been measured directly by sounding rockets and satellites, and during the fall I carried out work on mathematical and computer formulations of the problem in order to explain as many characteristics of the spacecraft data as possible. In particular I worked towards predicting the attenuation, absorption, reflection, dispersion, and polarization of Alfven wave fields as they interact with the ionosphere.

During the spring semester I will continue work on my computer simulation and data analysis, and I have made enough progress so that I can begin work on paper which I will submit for publication later this year.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Alan R. Levine

Semester: Spring 1989

University: Purdue University

Subcontract: S-789-000-040

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Title	Credit Hrs.	Grade
EE 695	Signal Image Processing	3	B
ME 687	Advanced Engineering Optics	3	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the Spring 89 semester my literature study on accurate remote 3-D optical measurement of parts for automated assembly operations was completed. Work was begun on defining the initial experimental studies.

"I certify that all information stated is correct and complete."

Alan Levine

Signature/Fellowship Recipient

Alan Levine

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5022C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Alan R. Levine is making satisfactory academic progress toward a Ph.D. in the area of Dynamic Control Systems in Robotics in the discipline of Mechanical Engineering for the Spring 1989 semester."

W H Stevenson

Signature/Advising Professor

Warren H. Stevenson
Professor of Mechanical Engineering
TYPED NAME/TITLE OF ADVISING
PROFESSOR

5022C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Alan R. Levine

Semester: Summer 1989

University: Purdue University

Subcontract: S-789-000-040

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   No courses were taken during the summer session.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   A study was begun on the nature of the image formed when imaging a laser illuminated spot on a metal surface under varied conditions. A GE Optomation II vision system linked to a VAX 11-780 computer is being used for image processing. This study will be continued during the 1989 Fall semester.

"I certify that all information stated is correct and complete."

Alan Levine

Signature/Fellowship Recipient

Alan Levine

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5022C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Alan R. Levine is making satisfactory academic progress toward a Ph.D. in the area of Dynamic Control Systems in Robotics in the discipline of Mechanical Engineering for the Summer 1989 semester."

W H Stevenson

Signature/Advising Professor

Warren H. Stevenson
Professor of Mechanical Engineering
TYPED NAME/TITLE OF ADVISING
PROFESSOR

5022C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Alan R. Levine Semester: Fall 1988

University: Purdue University Subcontract: S-789-000-040

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Title	Credit Hrs.	Grade
ME 563	Mechanical Vibrations	3	A
ME 575	Design of Control Systems	3	A
ME 587	Engineering Optics	3	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the Fall 88 Semester my primary effort was directed toward a literature survey on my dissertation topic -- accurate remote 3-D optical measurement of parts for automated assembly operations. The literature survey is now nearly complete and the details of the research program are being planned.

"I certify that all information stated is correct and complete."

Alan Levine 1/13/89
Signature/Fellowship Recipient

Alan Levine
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5022C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Alan R. Levine is making satisfactory academic progress toward a Ph.D. in the area of Dynamic Control Systems in Robotics in the discipline of Mechanical Engineering for the Fall 1988 semester."

W H Stevenson
Signature/Advising Professor

Warren H. Stevenson
Professor of Mechanical Engineering
TYPED NAME/TITLE OF ADVISING
PROFESSOR

5022C

CONCURRENCE FORM

The Aero Propulsion Laboratory requests the continuation of the AFOSR fellowship for Mr. Vincent G. McDonell, studying Spray andd Swirl Stabilized Flames at University of California, Irvine.

Give a brief statement of laboratory and/or Dr. W. M. Roquemore's (fellow's mentor) involvement with Mr. Vincent G. McDonell.

In January 1989 Mr McDonell spent two days at APPL discussing his proposed thesis project and touring our facilities. He gave a seminar entitled "Phase Doppler Measurements in Reacting and Nonreacting Flows" in which his past research was described and tentative plans for his dissertation were presented. Mr McDonell was to prepare a plan for his dissertation research and submit it to his advisor. From his current report, it appears that such a plan has been developed. We are pleased with the progress his is making.

Edward T Curran 14 Sep 89

Chief Scientist Date

W.M. Roquemore 8 Sept 89

Mentor Date

S-789-000-041

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Vincent McDonnell Semester/Academic Term: Spring '89

University: University of California Subcontract: S-789-000-041

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

(see attached sheet)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

(see attached sheet)

3. Give brief statement of your involvement with the Aero Propulsion Laboratory and Dr. Roquemore. Also list any items of interest such as academic awards, publications, other information that can be used for a LGFP newsletter.

(see attached sheet)

"I certify that all information stated is correct and complete."

Signature/Fellowship Recipient

Vincent G. McDonell
TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Vincent McDonnell is making satisfactory academic progress toward a Ph.D. in the area of Spray and Swirl Stabilized Flames for the Spring 1989 academic term."

GS Samuelsen

Signature/Advising Professor

G. S. Samuelsen, Prof. of Mech. and Envir. Engr.
TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

Spring Quarter 1989: April - June 1989

1. Course Work

Mechanical Engineering 235--Compressible Flow Grade: A

This class covered the basics of compressible flow and aimed at providing a complete set of tools for analyzing such flows. The class provided a good overview of the theoretical approaches and application of the approaches to practical situations.

Mechanical Engineering 232--Turbulence Grade: A-

This class covered detail derivation of the Reynolds averaged equations used in fluid mechanics. The continuity, momentum and energy equations were examined and the resulting kinetic energy and scalar transport equations were derived. The emphasis was on physical interpretation of the terms in the equations.

In addition to classes, the Ph.d. qualifying exam was taken and passed during the current reporting period.

2. Research done in support of dissertation

Summary of Research

Research conducted during the current reporting period was directed at literature surveys in the area of representative sprays, spray flames, and sprays in the presence of strong aerodynamics. One goal of the survey was to provide a concise concept of the research to be undertaken which will make a good contribution to the field.

The focus of the dissertation work will be examining the effect of different external factors on the behavior of the droplet/air flows produced by a representative atomizer. The work will examine, in great detail, the behavior of droplets and the relative effect of different external factors. Parameters to be considered will include (1) atomizer type (pressure or twin-fluid), (2) aerodynamic swirl, (3) reaction, and (4) orientation of the flow (up or down). Spatially and temporally resolved measurement of drop size, velocity, and trajectory will be made. In support of these measurement, species concentration and gas temperature will be measured. Finally, in the non-reacting cases, the amount of vapor present in the gas phase will be measured.

Much of the time during the quarter was spent developing a non-intrusive technique for measuring vapor concentration. The current approach utilizes a difference in the IR absorption spectra of liquid and gaseous methanol to measure the concentration of vapor. Initial assessment of the technique has demonstrated promise.

In support of the temporally resolved measurements, the droplet diagnostic system has been upgraded to provide time of event tagging and some time analysis capability. In addition, the system evaluation conducted in previous reporting periods has identified additional improvements which will also be incorporated into the system.

Also during the current reporting period, considerable effort was directed at identifying an atomizer to be used. Several candidates have been identified which will be obtained and screened during the next reporting period. It is desired to use an atomizer which has undergone detailed screening by the manufacturer so that issues of symmetry and poorly defined operating conditions can be avoided. Currently, an atomizer used in a previous program which was identified through considerable effort during the last reporting year will be considered. In addition, two nozzle manufacturers have been contacted and will provide "research" atomizers to be included in the screening studies.

Finally, efforts started in the area of numerical simulation. These efforts will be increased during the next reporting period.

3. Interaction with Laboratory Advisor

No significant interaction took place during the current reporting period

<u>Publications/Presentations</u>

McDonell, V.G. and Samuelsen, G.S., "Influence of the Continuous and Dispersed Phases on the Symmetry of a Gas Turbine Air-Blast Atomizer," to appear in Transaction of ASME Journal of Engineering for Gas Turbines and Power.

McDonell, V.G. and Samuelsen, G.S., "Application of Two-Component Phase Doppler Interferometry to the Measurement of Particle Size, Mass Flux, and Velocities in Two-Phase Flows," Twenty-Second Symposium (International) on Combustion, pp. 1961-1971.

CONCURRENCE FORM

The Aero Propulsion Laboratory requests the continuation of the AFOSR fellowship for Mr. Vincent G. McDonell, studying Spray andd Swirl Stabilized Flames at University of California, Irvine.

Give a brief statement of laboratory and/or Dr. W. M. Roquemore's (fellow's mentor) involvement with Mr. Vincent G. McDonell.

Mr. McDonell spent the 26 and 27 Jan. 1989 at WRDC/POSF. His progress on the Graduate Fellows Program was reviewed at this time. He gave a seminar entitled "Phase Doppler Measurements in Reacting and Nonreacting Flows." He is currently conducting spray research using Phase Doppler laser instumentation and as part of this thesis has coauthored a paper entitled "Influence of Continuous Phase on Fuel Distribution from a Gas Turbine Air-Blast Atomizer." This paper will be presented at the 2nd Annual Conference of the Institute of Liquid Atomization and Spray Systems, May 1988. Based on Mr McDonell's excellent performance, I recommend approval for his certification for the Student Fellows Program.

Edward T Curran

Chief Scientist Date

W. M. Roquemore 3 May 89

Mentor Date

S-789-000-041

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Vincent G. McDonell

University: The University of California, Irvine   Subcontract: S-789-000-041

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   (See attached sheets)

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   (See attached sheets)

"I certify that all information stated is correct and complete."

Signature/Fellowship Recipient

Vincent G. McDonell
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. Vincent G. McDonell is making satisfactory academic progress toward a Ph.D. in the area of Spray and Swirl Stabilized Flames in the discipline of Mechanical Engineering for the Fall 1988 quarter."

G Samuelsen
Signature/Advising Professor

Dr. G.S. Samuelsen, Prof. Mech. Engr.
TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4585C

Fall Quarter 1988: October - December 1988

1. Course work

No courses taken. Majority of quarter was spent completing existing contractual obligations.

2. Research done in support of dissertation

Summary of Research

During the current reporting period, substantial data were obtained in confined environments. The data consisted of particle-laden jet flows and represent a building block upon which numerical simulation can be applied to sprays. These data will be compared with modelling results to help understand the flows better and to build my confidence in the application of the numerical codes available (FLUENT, BYU-PCGC).

The experimental work done to verify the phase Doppler measurements of velocity in the previous reporting period was complemented by a similar study done on the spray. The results demonstrated the amount of uncertainty that might be expected from variation in the setting of certain parameters. These results were combined with the previous jet results into a paper which was presented at the ASTM Symposium on Liquid Particle Size Measurement Techniques. The paper was subsequently accepted for publication in a special technical publication.

Little experimental work was conducted in direct support of the dissertation. Instead, an in-depth literature review was started, with an emphasis on existing studies on spray combustion. The software started during the last reporting period was esentially completed during the current reporting period.

Papers

1. V.G. McDonell and G.S. Samuelsen, "Sensitivity Assessment of a Phase Doppler Interferometer to User Controlled Settings," presented at the ASTM 2nd Symposium on Liquid Particle Size Measurement Techniques, to appear in STP.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Vincent G. McDonell

University: The University of California, Irvine

Subcontract: S-789-000-041

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   (See attached sheets)

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   (See attached sheets)

"I certify that all information stated is correct and complete."

Vincent G. McDonell

Signature/Fellowship Recipient

Vincent G. McDonell

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. Vincent G. McDonell is making satisfactory academic progress toward a Ph.D. in the area of Spray and Swirl Stabilized Flames in the discipline of Mechanical Engineering for the Winter 1989 quarter."

G. S. Samuelsen

Signature/Advising Professor

Dr. G.S. Samuelsen, Prof. Mech. Engr.

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4585C

Winter Quarter 1989: January - March 1989

1. Course work

Physics 134--Introduction to Modern Optics. Grade: A+

This class was directed at physical understanding of optical phenomena such as light interaction with matter, laser principles, and applications of lasers to problem of interest in Physics. The class gave me some good background for design of optical systems, and applications that could be used in my dissertation work.

2. Research done in support of dissertation

Summary of Research

The current reporting period was directed at the development of a cohesive topic for the dissertation work. In support of this goal, I visited Wright Patterson Air Force Base and met with Drs. Roquemore and Jackson to discuss the possibility of my spending some time at the lab and doing research in spray combustion. It was decided that some area of overlap in interest definitely existed and that I could make use of the facility at Wright Patterson to measure temperature of the gas in the presence of droplets using CARS. This would provide me with a scalar measurement combined with simultaneous measurement of droplet size and velocity, which I would like to have as part of my dissertation work. The geometries available were discussed, and it was left for me to propose a testing condition to run at Wright Patterson.

The literature survey continued during the current reporting period, and an outline of the general plan for the dissertation was initiated. I have identified two candidate atomizers to be used in the work. One is a pressure atomizer, the other, an air-blast atomizer with which I have built a substantial data base in previous work. Methanol will be employed in the study owing to several desirable features including low vapor pressure, the ability to readily burn, and the mono-component nature of the liquid as a fuel.

I will need to modify the test facility to incorporate the pressure atomizer and to run reacting flow. The initial modifications made in support of the previous reacting flow study were judges adequate, and I need to formally establish the boundary conditions based upon these results. In support of the phase Doppler tests, patternation will be conducted to lend credence to the phase Doppler measurements of volume flux, which was previously identified in the ASTM work conducted during the last reporting period, to be the weak point of the phase Doppler approach. In addition, concepts for measurement of various scalars are being evaluated. In the non-reacting case, I want to measure the vapor concentration to provide better understanding of the vaporization process. Thus far, two approaches are being considered, one optical, and one intrusive. It is hoped that the optical approach will be successful. In the reacting case, either the measurement of a species or temperature, or both, will be conducted, and again both optical and intrusive techniques will be considered.

The experimental work conducted was directed at non-reacting confined sprays, and again provided experience upon which the dissertation work will be based. The results indicate satisfactory performance of the instrumentation. The move to upgrade the system to a 400 MHz clock was made during the current reporting period, and the transition to the upgrade will occur during the next reporting period.

In support of the droplet sizing measurements, software was written to better understand and to develop algorithms to deal with the issue of disparate optical sample volumes for drops of different size. This software will be applied as a tool for understanding errors in measurement of volume flux.

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mrs. Matilda Wilson McVay

University: Texas A&M University Subcontract: S-789-000-042

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

AERO 689 Symbolic Spacecraft Dynamics and Control (Grade A) Learn software for computer symbol manipulation with applications to problems in aerospace engineering.

CPSC 689 Software for Linear Analysis (Grade A) Matrix theory and computations including solutions of linear systems and computer applications.

MEEN 689 Control System Design (Grade A) Develop design techniques for control of linear systems using classical control theory and state space method

AERO 681 Seminar (Grade S - Satisfactory) Graduate research presented.

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

This semester I finished the course work required for my Ph.D. degree. I did computer based research on solutions of nonlinear dynamical systems. I developed a compiler type of FORTRAN code for a program which analytically derives a matrix of partial derivatives.

"I certify that all information stated is correct and complete."

Matilda Wilson McVay

Signature/Fellowship Recipient

Matilda Wilson McVay

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mrs. Matilda Wilson McVay is making satisfactory academic progress toward a Ph.D. in the area Space Craft Dynamics and Control in the discipline of Aerospace Engineering for the Spring 1989 semester."

John L. Junkins

Signature/Advising Professor

Dr. John L. Junkins

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4679C

TEXAS A&M UNIVERSITY/SYSTEM

COLLEGE STATION, TX 77843

DEPARTMENT OF
AEROSPACE ENGINEERING

215 OLD ENGINEERING
BUILDING
(409)845-7541

May 22, 1989

Mr. Rodney C. Darrah
Laboratory Graduate Fellowship Program
Universal Energy Systems
4401 Dayton-Xenia Rd.
Dayton, Ohio 45432-1894

Dear Mr. Darrah:

Enclosed is my academic progress report for the Spring 1989 semester. A transcript is being directly sent to you by the University.

Sincerely,

Matilda McVay

Matilda McVay

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Brian Milbrath Semester: Summer 1989

University: University of Virginia Subcontract: S-789-000-043

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Physics 997 - Non-topical Research - Summer research - P

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Please see the attached research report.

3. Give brief statement of your involvement with the Astronautics Laboratory Laboratory and Maj. Nordley.

Little direct involvement occured with the Astronautics Laboratory this summer. Dr. Thornton submitted a research proposal for funding to the U.S. Air Force.

"I certify that all information stated is correct and complete."

Brian D Milbrath

Signature/Fellowship Recipient

Brian D. Milbrath

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Brian Milbrath is making satisfactory academic progress toward a Ph.D. in the area of Antimatter in the discipline of Physics for the Summer 1989."

Stephen T. Thornton

Signature/Advising Professor

Dr. Stephen T. Thornton

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

A Study of Experimental Data and Computer Simulations Concerning the Interaction of Gamma-rays with Matter Resulting from Proton-Antiproton Annihilation

Brian D. Milbrath

University of Virginia Physics Department

October 4, 1989

Deep-space propulsion using antiprotons as an energy source has been deemed by the U.S. Air Force as a long-range possibility worthy of investigation. Since neither the supply of antiprotons nor scientific knowledge about them is very substantial, the U.S. Air Force is currently trying to generate interest in antiprotons and their many possible applications. Hopefully, more interest will lead to larger supplies of antiprotons and better estimates of their feasibility in space propulsion applications. Other possible uses include medical imaging, cancer therapy, industrial uses, and basic science.

Our ongoing antiproton research focuses on the study of the high-energy photons produced by an antiproton annihilation. The annihilation of an antiproton with a proton in matter produces neutral and charged pions. The neutral pions each quickly decay to two photons. Thus the equation of interest is:

$$\bar{p} + p \rightarrow \langle 3 \rangle \, \pi^{\pm} + \langle 3 \rangle \, \gamma$$

The spectrum of photon energies peaks at 70 MeV with an average at 200 MeV[1].

The first step in the research consisted of searching the literature for existing data. As it turns out, very few experiments involving gamma-ray-matter interactions at energies reasonably close to 200 MeV in energy have been performed. The following experimental measurements for photon absorption in the 100 MeV to 500 MeV range were found useful:

1) Lead and beryllium at 319 MeV by Anderson, et al[2].

2) Copper, tin, lead, uranium, beryllium, and aluminum at 280 MeV by DeWire, et al[3].

3) Carbon and aluminum at 100, 150, 200, and 250 MeV by Brookes, et al[4].

4) Carbon, aluminum, and titanium at 450 MeV with aluminum measured at 250 MeV as well by Miyachi, et al[5].

5) Copper, silver, and tantalum at 450 MeV by Miyachi, et al[6].

Despite the scarcity of experimental data, the theory of photon-matter interactions at these energies seems well understood and data derived from theoretical calculations are available. Useful compilations are provided by J. H. Hubbel of the National Institute of Science and Technology[7].

The present investigation compared the complilations with calculations done by computer programs using Monte Carlo techniques. Currently, such programs are used quite frequently by physicists to model planned experiments. We studied one of these programs to determine how well it worked in the region of interest. The program evaluated was EGS (Electromagnetic Gamma Shower) provided by SLAC. This evaluation is still ongoing. If such programs are deemed adequate, they may be used for engine and shielding design as research with antiprotons progresses.

The first test of EGS was to see how well it duplicated attenuation coefficients as calculated by Hubbell. This is a very simple problem and it was expected that EGS4 would get consistent results. Attenuation coefficients were calculated for the elements Al, Pb, Fe, Ag, and W. Several different energies were tried ranging from 1 MeV to 1000 MeV, and slab thicknesses ranged from 0.1 cm to 7.5 cm. Calculations for thicker slabs were unsucessful because of poor statistics. EGS was usually slightly low at low energies and slightly high at high energies and most accurate at approximately 100 MeV. Deviations ranged from 0.0 to 3.5%. The agreement between 50 MeV and 500 MeV, the approximate energy range for the antiproton annihilation gamma-rays, was 0.0 to 2.6%. An essential part of any Monte Carlo program is the random number generator, which must be given an initial number (known as a seed). Using this seed, a random number is calculated, which is then used as the seed for the next random number and so on. Using the same parameters with different initial seeds showed a range of approximately 1.0%.

Next EGS was tested to see if it could duplicate a known experiment in the region of interest. It was decided to model the experiment of Anderson, Kenney, and McDonald[2]. The experiment, as programmed into EGS and best determined from the article describing it, consisted of a beam of photons flatly distributed over a circle of 0.375 cm radius intersecting a 0.5 cm thick lead target. The energies of the photons prior to attenuation ranged evenly from 318.6 to 319.4 MeV. After traversing the target the photons traveled 99.5 cm through vacuum before reaching a collimator of radius 0.635 cm. Behind the collimator was a photon detector capable of detecting photons in the range of 319±8.4 MeV. Obviously, this was basically just an attenuation experiment. EGS result was in good agreement with the Hubbel tables value, with a total absorption cross-section of 37.336×10^{-23} cm^2 , which is slightly off of the result of $(37.62 \pm 0.225) \times 10^{-23}$ cm^2 obtained by the experiment.

The success of EGS in calculating the attenuation coefficients and duplicating the Anderson, Kenney, and McDonald experiment, as well as the success of these codes through the years implies that the theory of gamma-ray-matter interactions in the energy range of interest is well understood. Therefore, need for additional attenuation experiments in the energy range of interest does not seem warranted at this time, but may be in the future if attempts to use proton-antiproton annihilations continue to progress. However, in order to determine the usefulness of the existing programs for designing engines, shields, or other objects exposed to gamma-rays from proton-antiproton annihilations; a few of their aspects need further inspection. One such aspect is their ability to handle given geometries. EGS can be hard to use for complicated geometries so it would be beneficial to try modeling an engine with one of the available programs that has better geometric capabilities. Another aspect needing further investigation is the size limit of geometries that can be realistically handled by available computers. As mentioned in this article, if the slab thickness got too large poor statistics resulted. This can, of course, be remedied by using more computer time to get more statistics but one reaches a point where too much computer ' ne is being used.

BIBLIOGRAPHY

1) R. L. Forward, Antimatter Annihilation Propulsion, AFRPL Tr-85-034

2) J. D. Anderson, et al., Phys. Rev. 102, 1626 (1956).

3) J. W. DeWire, et al., Phys Rev. 83, 505 (1951).

4) G. R. Brookes, et al., Nuclear Physics A 94, 73 (1967).

5) T. Miyachi, et al., J. Phys. Soc. Japan 33, 577 (1972).

6) T. Miyachi, et al., J. Phys. Soc. Japan 34, 14 (1973).

7) J. H. Hubbell, et al., J. Phys. Chem. Ref. Data 9, 1023 (1980).

CONCURRENCE FORM

The School of Aerospace Medicine requests the continuation of the AFOSR fellowship for Mr. Thomas J. Mullen, studying Medical Engineering/Electrical Engineering at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. Fred Previc's (fellow's mentor) involvement with Mr. Thomas J. Mullen.

During the past year, Tom Mullen has visited USAFSAM and begun preparations for spending this summer working with scientists at USAFSAM/VN. Although he will be stationed in the Visual Orientation Laboratory, he will spend most of his time with Dr. Larry Krock developing and implementing a mathematical procedure for analyzing EKG data from lower-body negative pressure (LBNP) experiments. It is anticipated that he will also assist in running subjects in a visual-vestibular interaction study beginning in early June. His summer tenure will last approximately ten weeks.

2 Apr 89	28 Mar 89
Chief Scientist Date	Mentor Date

S-789-000-044

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Thomas J. Mullen

University: Massachusetts Institute of Technology

Subcontract: S-789-000-044

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   HST610 SYSTEMS ANALYSIS W/ PHYSIOLOGICAL APPLICATIONS
   HST595 TUTORIAL IN MED. ENG. AND MED. PHYSICS - PASS
   HST590 BIOMEDICAL ENGINEERING SEMINAR - PASS
   16.359 BIOENGINEERING JOURNAL ARTICLE SEMINAR - A

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   SEE ATTACHED SHEET

"I certify that all information stated is correct and complete."

Tom Mullen
Signature/Fellowship Recipient

THOMAS J. MULLEN
TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. Thomas J. Mullen is making satisfactory academic progress toward a Ph.D. in the area of Medical Engineering/Electrical Engineering in the discipline of Medical Engineering/Electrical Engineering for the Fall 1988 semester."

Signature/Advising Professor

MARTHA L. GRAY
TYPED NAME/TITLE OF ADVISING PROFESSOR

RESEARCH SUPERVISOR

C. M. OMAN, Sr. Res. Eng.

LLD/sdp 4698C

CERTIFICATION OF ACADEMIC PROGRESS

Response to Part 2:

Description of Research and Progress Towards Dissertation

The research area of general interest to my advisor and I is motion sickness. Previous thesis research in the laboratory has centered around the Electrogastrogram (EGG) and it's potential use as a diagnostic indicator or predictor of motion sickness. We have considered a number of different avenues of possible continued research and recently have settled on a line of research for my masters thesis - to use heart rate spectral estimation to investigate autonomic activity during motion sickness..

During the Fall term, 1988,

-- I completed the final report on a retrospective study of heart rate variability during motion sickness. (I began the study as a Research Assistant in the lab during the spring term and completed it over the summer.) In this study, I extracted an ECG component from abdominal potentials recorded during previous lab experiments in which subjects experienced varying degrees of prolonged motion sickness. I investigated power spectral estimation of heart rate variations and coefficient of variation of heart rate as two possible motion sickness indicators.

-- I continued a literature review of current motion sickness research and continued investigating statistical techniques for making multivariate classifications. One topic which was considered for my thesis research was the plausibility of using a number of physiological measures jointly in an attempt to diagnose or predict motion sickness onset.

-- In October, my advisor and I travelled to San Antonio to meet with Dr. Previk, my Air Force mentor. We discussed my progress and plans and possible summer research for 1989. We toured the School of Aerospace Medicine and met many of those involved in ongoing research. During the remainder of the term, we maintained communications with the goal of defining a summer research project. Further planning is necessary but it now appears that I will spend the summer working with Dr. Krock.

-- I worked to educate and equip a laboratory at the Massachusetts Eye and Ear Infirmary so that they are able to conduct motion sickness experiments. Our laboratory will benefit from this additional source of data.

-- I intensified discussions with Dr. Richard Cohen's Laboratory at MIT. We defined a joint project between the two laboratories which includes the experiments for my masters thesis. We propose to estimate the transfer functions of autonomic control of heart rate during motion sickness. Using a technique of inducing broad band respiratory input, we will "drive" the system over the band of physiologically important frequencies. The objective is to determine whether measurable changes in the transfer functions occur during sickness. Such changes would be attributed to changes in autonomic tone.

CONCURRENCE FORM

The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Todd Nichols, studying Measurement of Material Parameters at University of Colorado.

Give a brief statement of laboratory and/or Mr. ~~J. Earl Jones~~ Mark Calcatera (fellow's mentor) involvement with Mr. Todd Nichols.

Mr. Calcatera has assisted Mr. Nichols during the Summer term with his research topic into loss mechanisms of microstrip transmission lines on gallium arsenide substrates at microwave frequencies. During this time, Mr. Nichols completed the fabrication, design and initial testing of microstrip test structures on gallium arsenide wafers. This work has a high level of interest to this laboratory in view of its impact in the area of monolithic microwave integrated circuit technology. It is expected that Mr. Nichols will be able to continue this work during the next summer term.

[signature] 17 Oct 89
Chief Scientist Date

Mark Calcatera 6 Oct 89
Mentor Date

S-789-000-045

CERTIFICATION OF ACADEMIC PROG ;S

Fellow: Mr. Todd W. Nichols Semester: Fall 1988

University: University of Colorado at Boulder Subcontract: S-789-000-045

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   Clemson University:
   ECE 891 - 1 cr. - Master's Thesis Research - P (Pass)

   University of Colorado:
   ECEN 5210 - 3 cr. - Applied Math for Electrical Engineers - A
   ECEN 5144 - 3 cr. - Electromagnetic Boundary Value Problems - B+

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   * Master's thesis (for Clemson University) nearly complete.

   * Integral equation has been formulated for the benchmark numerical program for computing "exact" propagation constants in lossy stripline. A moment method solution will be used.

"I certify that all information stated is correct and complete."

Todd W. Nichols
Signature/Fellowship Recipient

Todd W. Nichols
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5028C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Todd W. Nichols is making satisfactory academic progress toward a Ph.D. in the area of Measurement of Material Parameters μ and ε in the discipline of Electrical Engineering for the Fall 1988 semester."

Signature/Advising Professor

Dr. John M. Dunn
TYPED NAME/TITLE OF ADVISING PROFESSOR

5028C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Brian Milbrath	Semester: Spring 1989

University: University of Virginia	Subcontract: S-789-000-043

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Electricity and Magnetism I - Electrostatics, magnetostatics, and Maxwell theory - A

Quantum Mechanics II - Perturbation theory, Scattering, and relativistic quantum mechanics - B

Statistical Mechanics I - Thermodynamics, kinetic theory, statistical ensembles. and B-E and F-D statistics - A-

continued on subsequent page ...

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the spring semester, I read much background material on antimatter research possibilities. Also, Dr. Thornton and I visited the Astronautics Laboratory, and Dr. Thornton attended the Antiproton Technology Workshop held at Brookhaven National Lab on May 12, 1989 to further help in selecting a research topic. The research chosen consists of the following areas:

1) Compile the existing photon absorption data for materials suitable for rocket engines at energies characteristic of proton-antiproton annihilations

continued on subsequent page ...

3. Give brief statement of your involvement with the Astronautics Laboratory Laboratory and Maj. Nordley.

In March, Dr. Thornton and I visited the Astronautics Laboratory. We talked with Major Nordley and the scientists there to help narrow down research possibilities.

"I certify that all information stated is correct and complete."

Brian D Milbrath

Signature/Fellowship Recipient

Brian D Milbrath

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

TELEPHONE:
924-3781

DEPARTMENT OF PHYSICS
UNIVERSITY OF VIRGINIA
MCCORMICK ROAD
CHARLOTTESVILLE, VIRGINIA
22901

1. cont.

Non-topical Research - Talks concerning research underway at the physics department - P

2. cont.

2) Model this data with Monte Carlo computer programs to see if existing data base sets and programming methods are adequate to reproduce experimental data.

3) Decide if further photon absorption measurement experiments are needed, and if so, plan them.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Brian Milbrath is making satisfactory academic progress toward a Ph.D. in the area of Antimatter in the discipline of Physics for the Spring 1989."

Stephen T. Thornton

Signature/Advising Professor

Stephen T. Thornton / Professor of Physics

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Todd W. Nichols, studying Measurement of Material Parameters at University of Colorado at Boulder.

Give a brief statement of laboratory and/or Mr. ~~J. Earl Jones's~~ Mark Calcatera's (fellow's mentor) involvement with Mr. Todd W. Nichols.

Mr. Calcatera is assisting Mr. Nichols with his research into loss mechanisms of microstrip lines on gallium-arsenide substrates. This involvement includes helping to formulate the research topic, guiding Mr. Nichols in the fabrication and measurement of test circuits, and review of analytical and measurement results for relevance and accuracy. This interaction occurs during Mr. Nichols stay at the Lab on a day-to-day basis. It is expected that Mr. Nichols will be able to complete the fabrication and testing of microwave loss of test circuits during this Summer term.

Ernie B. Champagne		Mark C Calcatera	12 Jun 8?
Chief Scientist	Date	Mentor	Date

S-789-000-045

CONCURRENCE FORM

The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Todd W. Nichols, studying Measurement of Material Parameters at University of Colorado at Boulder.

Give a brief statement of laboratory and/or Mr. J. Earl Jones's (fellow's mentor) involvement with Mr. Todd W. Nichols.

I have not been directly involved with Mr. Nichols this year, as he is currently spending a lot of time completing PhD level courses (as opposed to doing dissertation research), plus completing and preparing for defense of his Master's thesis.

The major problem has to do with the recent AFWAL - WRDC reorganization and security. Currently, Mr. Nichols does not possess a SECRET-level clearance, nor does the UES/AFOSR contract have a DD Form 254. With the reorganization, the Barn (formerly AFWAL/AAWP-3) is now a part of the Signature Technology Directorate (AFWAL/SNA). It is now the policy of this directorate that all who work in the Barn must have a SECRET-level clearance. This issue would prevent Mr. Nichols from working in the Barn, and possibly with our new organization.

To help rectify this problem so that Mr. Nichols could continue his involvement with the Air Force (Mr. Nichols is especially interested in doing a dissertation which would be of interest to the Air Force), see *.

In a recent telecon with Mr. Nichols (phone # 303-786-4934 at the Univ of Colorado), he has been working and has expressed interest in the MMIC/hybrid/materials/antennas areas. He has also been working at a MMIC Computer Aided Design (CAD) center at the Univ of Colorado, where he has been developing moment method theories/computer codes for microstrip structu[res] and attempting to experimentally verify these theories. He has been involved with loss mechanisms in planar structures and accounting for wave propagation in media with finite conductivity; for lossy media above perfect conductors.

Chief Scientist	Date	Mentor	Date
		J. Earl Jones AFWAL/SNA	2/15/89

* Since our new organization, in essence, precludes the use of Mr. Nichols, and since Mr. Nichols' interests are very compatible with the Electronics Technology Laboratories, which may be more cognizant of the Univ of Colorado MMIC CAD facility (which I understand is partially funded by DARPA), it is my opinion that ETL should seek a mentor to support Mr. Nichols. I have made this situation aware to Mr. Richard Remski, ETL Deputy Director. I have also discussed this matter with Mr. Les Lawrence (Avionics Lab Programs Office) with his concurrence.

S-789-000-045

CONCURRENCE FORM

The Electronic Technology Laboratory requests the continuation of the AFOSR fellowship for Mr Todd W. Nichols, studying Measurement of Material Parameters at the University of Colorado at Boulder.

In a recent telecon with Mr Nichols (6 Mar 89), Mr Calcatera, WRDC/ELM, discussed with Mr Nichols his research in finite element modeling of microstrip transmission lines and explained the nature of ELM's research in the microwave CAD and fabrication areas. It was agreed that the topic of mutual interest would be the "analysis and experimental verification of microstrip transmission line losses on gallium arsenide substrates." Mr Nichols expressed interest in working on this topic for the summer term of 1989 (beginning about 22 May) and Mr Calcatera agreed to serve as the mentor.

CHIEF SCIENTIST, DATE	MENTOR, DATE
Edwin B. Champagne 7 March 1989	Mark Calcatera 7 Mar 89
EDWIN B. CHAMPAGNE, Chief Scientist Electronic Technology Laboratory	MARK C. CALCATERA, Chief Microwave Techniques & Applications Branch Microwave Division

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Todd W. Nichols

Semester: Spring 1989

University: University of Colorado at Boulder

Subcontract: S-789-000-045

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

ECEN 5104 - Computer-Aided Design of Microwave Circuits:	A
ECEN 5904 - Finite Elements in Electromagnetics:	A
ECEN 5254 - Radar and Remote Sensing:	B+

(all courses are 3 credit hours each)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Passed both parts of Ph.D. preliminary exam in January.
Successfully defended master's thesis at Clemson in May.
Outlined experimental and theoretical goals for the summer at WPAFB such that they mesh with the project team at CU-Boulder.

"I certify that all information stated is correct and complete."

Todd W. Nichols
Signature/Fellowship Recipient

Todd W. Nichols
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5028C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Todd W. Nichols is making satisfactory academic progress toward a Ph.D. in the area of Measurement of Material Parameters μ and ε in the discipline of Electrical Engineering for the Spring 1989 semester."

Signature/Advising Professor

Dr. John M. Dunn
TYPED NAME/TITLE OF ADVISING PROFESSOR

5028C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Todd W. Nichols

Semester: Fall 1988

University: University of Colorado at Boulder

Subcontract: S-789-000-045

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   Clemson University:
   ECE 891 - 1 cr. - Master's Thesis Research - P (Pass)

   University of Colorado:
   ECEN 5210 - 3 cr. - Applied Math for Electrical Engineers - A
   ECEN 5144 - 3 cr. - Electromagnetic Boundary Value Problems - B+

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   * Master's thesis (for Clemson University) nearly complete.

   * Integral equation has been formulated for the benchmark numerical program for computing "exact" propagation constants in lossy stripline. A moment method solution will be used.

"I certify that all information stated is correct and complete."

Todd W. Nichols
Signature/Fellowship Recipient

Todd W. Nichols
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5028C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Todd W. Nichols is making satisfactory academic progress toward a Ph.D. in the area of Measurement of Material Parameters μ and ε in the discipline of Electrical Engineering for the Fall 1988 semester."

Signature/Advising Professor

Dr. John M. Dunn
TYPED NAME/TITLE OF ADVISING PROFESSOR

5028C

CONCURRENCE FORM

The Human Resource Laboratory requests the continuation of the AFOSR fellowship for Mr. Michael D. Richard, studying Image Processing at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. Walter Senus (fellow's mentor) involvement with Mr. Michael D. Richard.

Fred Diamond

Chief Scientist Date

Walter Senus 12/4/89

Mentor Date

S-789-000-046

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Michael D. Richard, studying Image Processing at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. Walter Senus's (fellow's mentor) involvement with Mr. Michael D. Richard.

During the summer of 89 Mr. Richard completed his summer reservist duty at RADC in the Intelligence and Reconnisance Directorate's Image Processing Laboratory. He worked with the staff in structuring the Directorate's program in neural network technology for the upcoming year. He presented his findings to Dr. Senus prior to his return to MIT. During the course of the year Dr. Senus and Mr. Richard keep up a continuous dialogue with at least monthly phone conversations. Mr. Richard's academic accomplishments were excellent during the fall semester, achieving an A in Analysis I with solid plans to complete Recursive estimation by the end of August. Adaptive Digital Filtering continuous to be Mike's principle interest. He has been approached by Prof. A. Oppenheim with a possible dissertation topic. Mike has until early September to accept or reject Prof. Oppenheim's offer.

Fred I Diamond

Chief Scientist Date

Walter J. Senus 8/8/89

Mentor Date

S-789-000-046

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael D. Richard   Semester: Summer 1989

University: Massachusetts Institute of Technology   Subcontract: S-789-000-046

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

No courses were taken during the summer (none of interest were offered.) Instead I concentrated on my thesis research.

However, I completed a paper — all 60 pages of it — on adaptive digital filtering in part to fulfill the requirements for a course on recursive estimation which I had taken in the spring. I received an A, both on the paper and for the course.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

During the summer, I investigated two complementary topics — adaptive digital filtering and active attenuation of acoustic noise. I summarize my findings in two comprehensive papers. The first, mentioned above, assessed and compared Finite-Impulse-Response (FIR) and Infinite Impulse-Response (IIR) adaptive filtering algorithms. The second examined the use of adaptive digital filtering for the active attenuation of acoustic noise.

"I certify that all information stated is correct and complete."

Signature/Fellowship Recipient

Michael D. Richard
TYPED NAME/FELLOWSHIP RECIPIENT

LLL/sdp 5023C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael D. Richard

Semester: Spring 1989

University: Massachusetts Institute of Technology

Subcontract: S-789-000-046

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

18.100B - Analysis I - Fundamentals of mathematical analysis. Convergence of sequences and series, continuity, differentiation, Riemann integral, sequences and series of fcns. - A

6.433 - Recursive Estimation - State- ~~based~~ space based theory of dyn estimation in discrete and continuous time. Kalman filtering and its many extensions (e.g. extended Kalman Filtering, square root information filter Grade withheld at my request pending completion of a paper on "adaptive filtering" which will summarize a portion of my summer research.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Initiated research on adaptive signal processing algorithms (both Finite-Impulse-Response and Infinite-Impulse-Response) and their utility for learning in neural networks. Research was impeded by extensive, painstaking preparation for the Oral ~~Equ~~ Qualifying Exam which I successfully completed in May.

"I certify that all information stated is correct and complete."

Signature/Fellowship Recipient

Michael D. Richard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5023C

CONCURRENCE FORM

The Rome Air Development Center requests the continuation of the AFOSR fellowship for Mr. Michael D. Richard, studying Image Processing at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Dr. Walter Senus's (fellow's mentor) involvement with Mr. Michael D. Richard.

Mr. Michael D. Richard and Dr. Senus have been in contact during the Academic semester. Dr. Senus has invited Mr. Richard to spend the summer at RADC to work in the Image Processing Lab. Mr Richard was unable to commit to this just yet due to both academic and personal commitments that may not allow him leaving MIT over the summer. It appears that Mr. Richard will be doing his summer reservist tour at RADC and will be assigned to the Intelligence Directorate, Dr. Senus' organization. Dr. Senus will continue to keep close contact with Mike in the hope of getting him back at RADC upon completion of his PhD program. Mr. Richard's progress toward his degree seems to be progressing very well . His course work(grades) are excellent, with a 5.0 average for the last semester. His qualifying examination efforts have also been successful, he has completed part one(written). Part two (oral) will be taken this May . His plans for a dissertation are solidifying .

Fred Diamond

Chief Scientist Date

Walter J. Senus 5/8/89

Mentor Date

S-789-000-046

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Michael D. Richard

Semester: Fall 1988

University: Massachusetts Institute of Technology

Subcontract: S-789-000-046

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

18.06 Linear Algebra - (Self explanatory) - A

6.866 Machine Vision - Intensive introduction to the process of generating a symbolic description of the environment from an image - A

9.382 Seminar on Visual Information Processing - Discussions (and guest presentat. of various computational problems in machine and biological vision - A

6.335 Theory of Nonlinear Systems - (No grades - Audited course)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Initiated research on use of artificial neural networks for motion vision. In conjunction with 6.866 and 9.382, completed a 25-page research paper analyzing existing work in this area and suggesting extensions of other neural network research with potential value in this area. Note: Much time (seemingly infinite) was devoted to preparing for a comprehensive written exam in January which constituted the first portion of the PhD qualify. exam.

"I certify that all information stated is correct and complete."

Signature/Fellowship Recipient

Michael D. Richard
TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5023C

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Frank E. Ritter　　　　Semester: Summer 1989

University: Carnegie-Mellon University　　　　Subcontract: S-789-000-047

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   No classes, just summer research.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Please see attached sheet.

"I certify that all information stated is correct and complete."

Frank E. Ritter

Signature/Fellowship Recipient

Frank E. Ritter

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5024C

2. Description of Research and Progress toward Dissertation

The draft paper reporting the results of my first and second year experiments was further revised. Prof. Lynne Reder (a member of my committee) and I hope to submit it for publication to the Journal of Experimental Psychology: Learning, Memory and Cognition early this fall. While rewriting we found that several of the analysis had to be recomputed, mostly with minor changes. The new analyses are consistent with the initial analyses' results.

Working with Soar, a unified theory of cognition realized as a production system, seems more difficult than we think it should. To make programming it easier I wrote an extension to a common editor. The extension provides several commands for manipulating Soar programs more quickly and easily than before.

I also drafted a review paper called "A unified theory of feeling-of-knowing". This paper fulfilled the requirement in our Ph.D. program of writing a review paper during the summer between the 2nd and 3rd years. It is now out with my committee and I am awaiting their comments before revising it, and either submitting it, or passing it around informally.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Frank E. Ritter is making satisfactory academic progress toward a Ph.D. in the area of Models of Cognitive Processes in the discipline of Psychology for the Summer 1989 semester."

Allen Newell 10 Oct 89

Signature/Advising Professor

Professor Allen Newell

TYPED NAME/TITLE OF ADVISING PROFESSOR

5024C

CONCURRENCE FORM

The Human Research Labortory requests the continuation of the AFOSR fellowship for Mr. Frank E. Ritter, studying Models of Cognitive Processes at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Valerie Shute's (fellow's mentor) involvement with Mr. Frank E. Ritter.

AFHRL/MOEL has been kept informed of Frank Ritter's research in cognitive processes and strategies. He sent us some preliminary results/analyses from a study he conducted at CMU involving the solution of multiplication problems as a function of sequential presentations of the same problem. Subjects could elect to calculate or retrieve a response and then indicate which strategy they employed.

Frank appears to be progressing very well in his academic and research endeavors. Because it is early in his graduate career, he is mostly involved with classwork. We are looking forward to more interaction with him in the future once his classwork is behind him. For instance, he has indicated that he would like to spend next summer (FY90) here at HRL conducting some research that is complementary to our basic research interests.

George Moeller 20 Jul 89 | Valerie J Shute 7 July 89

Chief Scientist Date | Mentor Date

S-789-000-047

/

CONCURRENCE FORM

The Human Resources Laboratory requests the continuation of the AFOSR fellowship for Mr. Frank E. Ritter, studying Models of Cognitive Processes at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Valerie Shute (fellow's mentor) involvement with Mr. Frank E. Ritter.

AFHRL/MOEL has been kept informed of Frank Ritter's research in cognitive processes and strategies. He has continued to excel in his studies, as indicated by his professors, and is writing significant papers in the field of cognitive psychology. Moreover, after working with Soar (a unified theory of cognition embodied within a large compute program), and determing areas of weakness within the program/interface, Frank wrote an extension to a common editor for manipulating Soar programs more quickly and easily than before. So Frank is evolving and succeeding along many productive fronts.

11/29/89
Chief Scientist Date

Valerie Shute Nov 20 1989
Mentor Date

S-789-000-047

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Frank E. Ritter | Semester: Spring 1989

University: Carnegie-Mellon University | Subcontract: S-789-000-047

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Psychology Graduate Core Courses, Developmental Quarter, 85-710, B+, Winter 1988-89.

Psychology Graduate Core Courses, Social Quarter, 85-710, B+, Spring 1988-89.

Supervised research and readings, 85-781, Prof. Newell, A, Spring 1988.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

(Please see attatched sheet.)

"I certify that all information stated is correct and complete."

Frank E. Ritter

Signature/Fellowship Recipient

Frank E. Ritter 6/22/89

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5024C

2. Description of Research and Progress toward Dissertation

With Prof. Lynne Reder (a member of my committee) and her research assistants I ran a second experiment this spring on feeling-of-knowing. The data analysis is complete, and it confirms the results of my first experiment. We found that feelings-of-knowing for arithmetic problems increase linearly with respect to knowing in a regular environment, but that it is actually based on familiarity with the parts of the problem, rather than actual knowledge of the answer. I have drafted a paper reporting these results, and it is serially circulating among my committee. Lynne and I anticipate submitting it to a journal sometime this summer.

This spring I wrote a Soar model of the feeling-of-knowing data, and presented it twice, as a Brown Bag (2nd year graduate student talk), and at a small workshop held at the University of Michigan for the Soar research group. Each time I received useful feedback. It needs more work, but it looks promising and I feel much more in command of Soar.

The paper needs to taken from draft form to a full paper ready for submission. There are several aspects of the Soar model of feeling-of-knowing that are clear in my mind, but need to be implemented.

Citations of papers and presentations, Spring 1989

Ritter, Frank (joint work with Lynne Reder), "The Effect of Feature Frequency on Feeling-of-knowing and Strategy Selection for Arithmetic Problems," Second year graduate program presentation and paper; draft, under revision for submission.

Ritter, Frank, (joint work with Lynne Reder, including some comments of Allen Newell) "Modeling a Feeling-of-knowing", presented at the Soar VI workshop held in May 1989 at the University of Michigan.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Frank E. Ritter is making satisfactory academic progress toward a Ph.D. in the area of Models of Cognitive Processes in the discipline of Psychology for the Spring 1989 semester."

Allen Newell

Signature/Advising Professor

Allen Newell 6/12/89

TYPED NAME/TITLE OF ADVISING PROFESSOR

5024C

CONCURRENCE FORM

The Human Research Labortory requests the continuation of the AFOSR fellowship for Mr. Frank E. Ritter, studying Models of Cognitive Processes at Carnegie-Mellon University.

Give a brief statement of laboratory and/or Dr. Valarie Shute's (fellow's mentor) involvement with Mr. Frank E. Ritter.

Frank Ritter and I have been in touch over the phone, through the mail, and by e-mail since before July, 1988. He came to AFHRL Sep 88 to deliver a talk to LAMP about his current doctoral research being conducted at CMU using Newell's SOAR model of cognition/learning. His current research interests center around a "feeling of knowing" phenomenon being conducted in conjunction with Prof Lynn Reder, CMU. In collaboration with AFHRL, Frank has expressed interest in mathematically modelling some of the data from the PASCAL programming tutor in relation to students' progress through tht tutor (i.e., their learning efficiency rates) based on the elementary cognitive processes involved in the solutions as well as the relative difficulty levels of the problems in the curriculum.

Chief Scientist Date

4/14/89

Mentor Date

S-789-000-047

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Frank E. Ritter Semester: Fall 1988

University: Carnegie-Mellon University Subcontract: S-789-000-047

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Psychology Core Courses, Developmental Quarter, 85-710, Winter 1988-89.

Perception, 85-420, Prof. Granrud, Audit, Fall 1988.

Supervised research and readings, 85-781, Prof. Newell, A, Fall 1988.

Teaching Practicum, for Research Methods in Cognitive Psychology, 85-310, Prof. Reder, grader for tests and papers, designed mid-term and final test questions, gave several short lectures, assisted students with lab design and analysis, evaluated alternative text books; A, Fall 1988.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

(Please attatched sheet.)

"I certify that all information stated is correct and complete."

Frank Ritter

Signature/Fellowship Recipient

Frank Ritter

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5024C

2. Description of Research and Progress toward Dissertation

The feeling-of-knowing experiment with Prof. Lynne Reder (a member of my committee) has been run and the data analyzed. We have found some interesting effects, for example, that feeling-of-knowing for arithmetic problems appears to be based on familiarity with the parts of the problem, rather than actual knowledge of the answer. I am rewriting my first year paper with Lynne with an eye towards publishing these results, or minimally, having a paper that we can send to the people who requested a written version of our talk at Psychonomics.

The next step is to start in earnest to model the Feeling-of-knowing arithmetic task in Soar. In addition to the direct application this will have on my (our) FOK research, it will be a large enough project to force me to truly understand Soar. Lynne and I are also looking into running another experiment in order to make our results a more tidy and publishable package.

Citations of papers and presentations, Fall 1988

Reder, Lynne, & Ritter, Frank, "The effect of Feature Frequency on Feeling-of-knowing and Strategy Selection for Arithmetic problems," revised version of First year paper, in preparation for possible submission.

Reder, Lynne, & Ritter, Frank, "Feeling-of-Knowing and Strategy Selection for Solving Arithmetic Problems," talk presented at the Psychonomics Fall 1988 Conference", abstract included in proceedings (enclosed).

Ritter, Frank, "ITS and Modeling the Seibel Task in Soar," presentation at the Air Force Human Resources Lab, Cognitive Skills Assessment Branch, Brooks AFB, September, 1988.

Ritter, Frank, "Update on the Seibel task," presented at the Soar V workshop held in September 1988.

Ritter, Frank, "OREO: Orienting Electrical Circuits for Qualitative Reasoning," BBN Technical Report #6560, 1987, submitted to <u>AI and Education</u>.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Frank E. Ritter is making satisfactory academic progress toward a Ph.D. in the area of Models of Cognitive Processes in the discipline of Psychology for the Fall 1988 semester."

Allen Newell 28 Mar 89

Signature/Advising Professor

Prof.Allen Newell

TYPED NAME/TITLE OF ADVISING PROFESSOR

5024C

CONCURRENCE FORM

The Weapons Laboratory requests the continuation of the AFOSR fellowship for Mr. Thomas A. Spencer, studying High Power Microwaves at The University of Michigan.

Give a brief statement of laboratory and/or Dr. William Baker's (fellow's mentor) involvement with Mr. Thomas A. Spencer.

Dr Kit Hackett and myself have been working with Mr Spencer during his summer work period at the Weapons Laboratory. He is learning to use the MAGIC computer code to numerically simulate a high power microwave device. He will apply this knowledge to the experiment at the Univ of Michigan when he returns. Besides his computational work he is also working in the laboratory setting up and using sophisticated diagnostic and instrumentation. He is making excellent use of his time here in furthering both our projects and his education.

Carl Edward Oliver | William L Baker 22 Jun 89

Chief Scientist | Date | Mentor | Date

CARL EDWARD OLIVER, Lt Col, USAF
Deputy Chief Scientist 26 Jun 89

S-789-000-048

Atch #1

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Thomas A. Spencer

University: The University of Michigan Subcontract: S-789-000-048

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   See attached sheet.

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   See attached sheet.

"I certify that all information stated is correct and complete."

Thomas A. Spencer

Signature/Fellowship Recipient

Thomas A. Spencer

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. Th^mas A. Spencer is making satisfactory academic progress toward a Ph.D. in the area of High Power Microwaves in the discipline of Nuclear Engineering for the Winter 1989 term."

Ronald M. Gilgenbach

Signature/Advising Professor

Dr. Ronald M. Gilgenbach

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4678C

Continuation of Certification of Academic Progress

Fellow: Thomas A. Spencer
The University of Michigan — Subcontract: S-789-000-048
Date: April 27, 1989

1) Courses:

A) **NE 572** (Nuclear Engineering 572): Principles of Plasma Physics II. Studied: Fokker-Planck equation for plasmas; Calculations of Relaxation times from the F-P eqn.; The use of the Boltzmann equation; P-1 equations; Lorentz Gas Model; Electrical conductivity in weakly ionized plasma; Calculation of diffusion coefficient; Fluctuations, correlations and radiation of plasmas; test particle theory of correlations; 'dressed' particle theory applications to correlation functions; analysis of light scattering in plasmas from 'dressed' particle thoery.

Grade: A+
Credit Hours: 3

B) **EECS 533** (Electrical Engineering and Computer Science 533): Microwave Measurements Lab. Used an HP8510 Network Analyzer to perform the following labs: Dipole antenna design and measurements; Microstrip antenna design and measurements; Radar cross-section measurements; Dielectric constant measurements; Polarimetric radar measurements (using an HP8753 Network Analyzer); Microwave Imaging Experiments (imaging model airplanes).

Grade: A-
Credit Hours: 2

C) **EECS 630** (Electrical Engineering and Computer Science 630): Electomagnetic Theory II. Studied transforms; Maxwell's equations; Propagation in homogeneous and inhomogeneous media (crystals, ionosphere, near the earth); Multipole radiation; Special relativity: relativistic Doppler shift, fields in moving systems; Radiation from moving charges: Synchrotron, Bremsstrahlung and Cerenkov emission, classical damping and level shifts; Scattering, cross sections, coherent vs. incoherent, scattering from free electrons, bound electrons (atoms), sound waves and spheres.

Grade: A
Credit Hours: 3

D) **NE 990** (Nuclear Enginnering 990): Pre-Candidate Research/Dissertation. Continued research on the MELBA high power microwave (HPM) experiment including cavity design studies for interaction region of beam and waves, actual running of the experiment where we obtained good results of HPM in the J-, X-, and K-bands of the microwave frequency spectrum. Looks like lower MW power in the J- and K-band (appears to be in the TE_{11} mode) and upper kW power in the X-band (appears to be in the competeing TE_{21} mode). Exact power calibration measurements are being conducted to get exact power measurements for these bands. New design studies for a new solenoid and interaction region to optimize the beam-cavity wave interaction for higher efficiency are being performed.

Grade: S (Satisfactory; no letter grades (that is A-E) are given for this class, only the credit hours are recorded towards the PhD degree.)
Credit Hours: 3

Continuation of Certification of Academic Progress

Fellow: Thomas A. Spencer
The University of Michigan Subcontract: S-789-000-048
Date: May 17, 1989

2) Research and progress towards dissertation:

Continued research on the MELBA high power microwave (HPM) experiment including cavity design studies for interaction region of beam and waves, and continued construction of the experimental set-up on MELBA. Participated in high power microwave cyclotron autoresonance maser (CARM) experiments (electron beam parameters of 0.4 MeV, 1 kA). Performed HPM experiments on MELBA (beam parameters of 0.7 MeV, 2-10 kA) in which we obtained good results of high power microwave generation in the J-band (4.3 - 6.6 GHz), X-band (6.6 - 14.1 GHz), and K-band (14.1 ~ 40.0 GHz) of the microwave spectrum. High power microwave radiation in the J- and K-band (appears to be in the TE_{11} mode) has been obtained, along with high (but less than the J- and K-bands) power radiation in the X-band (appears to be in the competing TE_{21} mode). Power calibration measurements are being conducted to get more accurate power measurements for these bands. Design studies for a new solenoid and interaction region to optimize the beam-cavity wave interaction for higher efficiency are being performed.

Also, passed written Ph.D. preliminary examination taken on May 12, 1989. Passing grade approved on May 17, 1989.

Thomas A. Spencer
298 Village Green Blvd. #202
Ann Arbor, MI 48105

May 15, 1989
UES, Inc.
ATTN: Rodney C. Darrah
4401 Dayton-Xenia Rd
Dayton, Ohio 45432-1894

Subject: Certification of Academic Progress;
Contract No. F49620-86-C-0127/SB5861-0436
Subcontract No. S-789-000-048

Dear Mr. Darrah:

Enclosed within is my Certification of Academic Progress for theWinter 89 term beginning January 1, 1989 and ending April 30, 1989. The University of Michigan is also sending the latest copy of my transcript, which should arrive in the near future.

Thanks for your time,

Sincerely,

Thomas A. Spencer

THE GRADUATE SCHOOL
Cornell University
SAGE GRADUATE CENTER
ITHACA, NEW YORK 14853-6201

May 30, 1989

Mr. Rodney Darrah
Program Manager
Laboratory Graduate Fellowship Program
Universal Energy Systems, Inc.
4401 Dayton-Xenia Road
Dayton, OH 45432-1894

Dear Mr. Darrah,

I am enclosing the Spring 1989 Progress Report Forms for Mr. David Knudsen. It is my understanding that a statement of progress must be filed with you for those students who are receiving a Universal Energy Systems Fellowship.

I hope that all of the necessary paperwork is in order. Please do not hesitate to contact me should you require further information

Sincerely yours,

Joanne Bordonaro

Joanne S. Bordonaro
Director
Graduate Fellowship &
Financial Aid Office

JSB/sss

CONCURRENCE FORM

The Weapons Laboratory requests the continuation of the AFOSR fellowship for Mr. Thomas A. Spencer, studying High ower Microwaves at The University of Michigan.

Give a brief statement of laboratory and/or Dr. William Baker's (fellow's mentor) involvement with Mr. Thomas A. Spencer.

Dr Hackett from AFWL/AWPP visited the University of Michigan on 10 March, 1989 to review Dr Gilgenbach's research and talk to Mr Spencer.

Mr Spencer is working for Dr Gilgenbach at the University of Michigan in the area of High Power Microwaves. Mr Spencer is presently working on the design and cold testing of cavities. The purpose of these cavities is to enable the interaction of a high power electron beam with electromagnetic modes of the cavity. The particular cavity designs which Mr Spencer is constructing are slotted to preferentially damp undesired modes. If Mr Spencer's work is successful, the microwave tube will oscillate in a single mode with higher output power than the tube presently exhibits.

We find that Mr Spencer is continuing to perform excellent research under Dr Gilgenbach's guidance and is making steady progress towards his doctorate. Mr Spencer's research in High Power Microwaves is very interesting to the Air Force Weapons Laboratory. Request Mr Spencer's AFOSR fellowship be continued.

Carl Edward Oliver — William L Baker 13 Mar 89

Chief Scientist Date — Mentor Date

20 MAR 1989

S-789-000-048

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Thomas A. Spencer

University: The University of Michigan   Subcontract: S-789-000-048

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   See attached sheet.

2. Give a detailed description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   See attached sheet.

"I certify that all information stated is correct and complete."

Thomas A. Spencer

Signature/Fellowship Recipient

Thomas A. Spencer

TYPED NAME/FELLOWSHIP RECIPIENT

"I certify that Mr. Thomas A. Spencer is making satisfactory academic progress toward a Ph.D. in the area of High Power Microwaves in the discipline of Nuclear Engineering for the Fall 1988 term."

Ronald M. Gilgenbach

Signature/Advising Professor

Dr. Ronald M. Gilgenbach,

TYPED NAME/TITLE OF ADVISING PROFESSOR

LLD/sdp 4678C

Continuation of Certification of Academic Progress
Fellow: Thomas A. Spencer
The University of Michigan — Subcontract: S-789-000-048
Date: January 31, 1989

1) Courses:

NE 571 (Nuclear Engineering 571): Princples of Plasma Physics. Studied: statistical description plasmas, Lorentz-Maxwell equations, Klimontovich-Dupree eqn., Hamiltonian formulism; Equilibrium properties of plasmas, Debye shielding, plasma capacitors, mean Coulomb energy of a plasma, static form factor, pair correlation function; Non-equilibrium properties of plasmas, solutions of linearized Vlasov-Maxwell eqns.; Plasmas as a dielectric medium, wave propagation in field-free and external field plasmas; Vlasov theory of plasma stablity, plasma instabilities, bunching, energy exchange between plasmas and waves.

Grade: A
Credit Hours: 3

NE 576 (Nuclear Engineering 576): Principles of Charged Particle Accelerators. Studied electrostatic and electrodynamic accelerator principles; magnetic and electrostatic focusing of relativistic particles; transient analysis of pulsed accelerators; Poisson/Laplace analysis of accelerator systems and components; electron beam cathodes; ion beam sources; engineering aspects of field emission, insulator flashover, and vacuum arc phenomena; computer analysis of circuitry for accelerator using SPICE computer code (on APOLLO computers).

Grade: A
Credit Hours: 3

EECS 530 (Electrical Engineering and Computer Science 530): Electormagnetic Theory. Studied transforms; Maxwell's equations; electrostatics, Green's functions, boundary conditions, expansions for Green's functions, multipoles; magnetostatics, motion of charges in electric and magnetic fields; time-varying fields, gauge transformations (Lorentz and Coulomb), Poynting vector, Green's functions for dynamic fields; concepts in waveguides, antennas, cavities, and associated theorems; plane wave propagation, regular antennas, aperture antennas and arrays, waveguides and mode expansions, and diffraction.

Grade: A-
Credit Hours: 3

NE 990 (Nuclear Enginnering 990): Pre-Candidate Research/Dissertation. Continued research on the MELBA high power microwave (HPM) experiment including new design parameters for the solenoid (and constructed for these parameters), circuit studies for the pulser for the solenoid, cavity design studies for interaction region of beam and waves, continued construction of the experimental set-up on MELBA.

Grade: S (Satisfactory; no letter grades (that is A-E) are given for this class, only the credit hours are recorded towards the PhD degree.)
Credit Hours: 3

Note: With the completion of this term, I successfully completed the requirements for a Master's of Science in Nuclear Engineering which I received as of Dec. 18, 1988.

Continuation of Certification of Academic Progress

Fellow: Thomas A. Spencer
The University of Michigan
Date: January 31, 1989

Subcontract: S-789-000-048

2) Reasearch and progress towards dissertation:

Continued research on the MELBA high power microwave (HPM) experiment including new design parameters for the solenoid (and constructed for these parameters), circuit studies for the pulser for the solenoid, cavity design studies for interaction region of beam and waves, continued construction of the experimental set-up on MELBA. Participated in high power microwave experiments (electron beam parameters of 0.4 MeV, 1 kA) which are being used as a guideline for the MELBA (beam parameters of 1.0 MeV, 10 kA) HPM experiment, the results of which will be printed at a later date. Also attached to this continuation are two copies of an abstract entitled **High Power Microwave Emission from Cyclotron Autoresonance Maser (CARM) Interactions in Microsecond, Intense Electron Beams** by R.M. Gilgenbach, J.G. Wang, J.J. Choi, C.A. Outten, and T. Spencer, submitted to the Sixteenth IEEE International Conference on Plasma Science to be held on 22-24 of May (1989) in Buffalo, New York.

The completion of classes for the Fall term of 1988 completed my requirements for a Master's of Science in Nuclear Engineering, which I received as of Dec. 18, 1988, and has changed my status to Pre- Candidate in my continued progress towards my dissertation.

High Power Microwave Emission from Cyclotron Autoresonance Maser (CARM) Interactions in Microsecond, Intense Electron Beams *

R. M. Gilgenbach, J. G. Wang, J. J. Choi,
C. A. Outten, and T. Spencer
Intense Energy Beam Interaction Laboratory, Nuclear Engineering Department, University of Michigan, Ann Arbor, MI
48109-2104

Experiments have been performed in which multimegawatt, frequency tunable, microwave radiation has been generated in the K-band and X-band by means of cyclotron maser mechanisms on intense electron beams with microsecond pulselengths. The masers operate as oscillators with cylindrical cavities in the TE_{11n} modes or TE_{01n} modes. Experiments have been performed utilizing two long pulse, intense electron beam accelerators. Initial experiments used a generator with parameters: voltage = 0.4 MV, current = 1 kA, and pulselength = 0.3-0.4 μs. These experiments have generated over 3 MW of K-band microwave radiation, magnetically tunable from 14 GHz through 15.5 GHz. The frequency of this radiation corresponds to the cyclotron autoresonant maser (CARM) forward wave interaction. In the same experiments we observed MW level X-band radiation, magnetically tunable from 10-12 GHz. The frequency of this emission indicates that it originates from the cyclotron maser backward wave interaction or absolute instability. Microwave pulselengths of 0.1μs to 0.2μs were generated in these initial experiments. Experiments are currently underway on the Michigan Electron Long Beam Accelerator (MELBA), with operating parameters : 0.8-1 MV, 1-10 kA, and pulselength adjustable between 0.3 to 1.5 μs.

* This research was sponsored in part by the Air Force Office of Scientific Research, Air Force Weapons Laboratory, and the National Science Foundation.

CONCURRENCE FORM

The Materials Laboratory requests the continuation of the AFOSR fellowship for Mr. Keith P. Walley, studying Tribology at University of Illinois at Urbana-Champaign.

Give a brief statement of laboratory and/or Mr. Walt Haas's (fellow's mentor) involvement with Mr. Keith P. Walley.

Prof. Andrew Gellman has presented results of Mr. Keith Walley's research on the surface chemical and tribological properties of various long chain organics at the AFOSR surface chemistry reviews. Discussions were held on this work at this meeting as well as at the Tribology Workshop here in Dayton as well.

[signature]		G W Haas	20 Dec 89
Chief Scientist	Date	Mentor	Date

S-789-000-050

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Keith P. Walley

Semester: Spring 1989

University: University of Illinois
at Urbana-Champaign

Subcontract: S-789-000-050

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   During the spring semester, I took Chem 445 and Chem 499. Chem 445 is Physical Chemistry Seminar, a course required of physical chemistry graduate students at my school in which each enrolled student presents a seminar on his or her research to an unrestricted audience. The course is graded in a "satisfactory vs. unsatisfactory" fashion, and I received an "S," which ~~obviously stands for "satisfactory."~~ For Chem 499, which is Thesis Research in Chemistry, I received a mark of "DF," which not-so-obviously stands for "grade deferred until the completion of thesis research." This is the usual grade received by a student enrolled in Chem 499 until the completion of his or her dissertation.

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   Please see the appended sheets.

"I certify that all information stated is correct and complete."

Keith Paul Walley

Signature/Fellowship Recipient

Keith Paul Walley

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5029C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Keith P. Walley is making satisfactory academic progress toward a Ph.D. in the area of Tribology in the discipline of Chemistry for the Spring 1989 semester."

A. Gellman

Signature/Advising Professor

Andrew J. Gellman, Assistant Professor of Chemistry

TYPED NAME/TITLE OF ADVISING PROFESSOR

5029C

CONCURRENCE FORM

The Geophysics Laboratory requests the continuation of the AFSOR fellowship for Mr. Rodger J. Biasca, studying Space Physics at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Mr. Charles Pike's (fellow's mentor) involvement with Mr. Rodger J. Biascia.

Mr. Biasca is involved in a project to develop new numerical methods for multiple time scale simulation of plasma phenomena, in particular the Critical Velocity Ionization mechanism under space-like conditions. We are incredibly pleased with his work to date. Rodger works in close cooperation with myself, and visits AFGL one to two days per week plus regular telephone contact from MIT where he is a graduate student. His summer schedule has him here at the lab daily which has allowed us the cooperate very closely on his development of an implicit Particle-in-Cell simulation code.

for A. S. Jursa 10 July 89 — Chief Scientist, Date

David L. Cooke 7 July 89 — Mentor, Date

S-789-000-051

CERTIFICATION OF ACADEMIC PROGRESS

Fellow:

Mr. Rodger J. Biasca

Semester: Spring 1989

University: Massachusetts Institute of Technology

Subcontract: S-789-000-051

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Intro to Plasma Physics II	A
Space Propulsion and Power	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

My research involves developing a particle-in-cell computer code in order to investigate the critical ionization velocity (CIV) effect observed in plasmas. This term was spent creating an implicit version of the explicit particle-in-cell code I completed last semester. In order to investigate the time scales of interest in the CIV effect, an implicit code will be a necessity. Currently, I am working on test cases to assure the proper functioning of the code.

3. Give brief statement of your involvement with the Geophysics Laboratory and Mr. Charles Pike.

I have been visiting AFGL about once a week throughout the term. Most of my involvment with AFGL has been with Dr. David Cooke. My discussions with him have been invaluable to my progress on my dissertation. The AFGL has provided a source of considerable experience in working with particle codes and their applications.

"I certify that all information stated is correct and complete."

Rodger J. Biasca

Signature/Fellowship Recipient

Rodger J. Biasca

TYPED NAME/FELLOWSHIP RECIPIENT

2094t

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Rodger J. Biasca is making satisfactory academic progress toward a Ph.D. in the area of Space Physics in the discipline of Aeronautics and Astronautics for the Spring 1989 semester."

Daniel Hastings

Signature/Advising Professor

Daniel Hastings, Class of 1956 Career Development Associate Professor of Aeronautics and Astronautics

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

CONCURRENCE FORM

The Geophysics Laboratory requests the continuation of the AFOSR fellowship for Mr. Rodger J. Biasca, studying Space Physics at Massachusetts Institute of Technology.

Give a brief statement of laboratory and/or Mr. Charles Pike's (fellow's mentor) involvement with Mr. Rodger J. Biasca.

Mr. Biasca is involved in a project to develop new numerical methods for multiple time scale simulation of plasma phenomena, in particular the Critical Velocity Ionization mechanism under space-like conditions. We are incredibly pleased with his work to date. Rodger works in close cooperation with myself, and visits AFGL one to two days per week plus regular telephone contact from MIT where he is a graduate student.

16 May 89   David L. Cooke 15 May 8

for Chief Scientist   Date   Mentor   Date

S-789-000-051

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. Rodger J. Biasca | Semester: Fall 1988

University: Massachusetts Institute of Technology | Subcontract: S-789-000-051

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Real Gas Dynamics	A
Intro. to Plasma Physics I	B

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

My research focuses on developing computational methods suitable for use in investigating critical ionization velocity and other medium to low frequency phenomena in atmospheric plasmas. Since this was the first semester of my dissertation research, much of my work was focused on surveying the literature and developing a simple explicit two-dimensional particle-in-cell program that will form the basis for more elaborate codes in the future.

"I certify that all information stated is correct and complete."

Rodger J. Biasca

Signature/Fellowship Recipient

Rodger J. Biasca

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5025C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Rodger J. Biasca is making satisfactory academic progress toward a Ph.D. in the area of Space Physics in the discipline of Aeronautics and Astronautics for the Fall 1988 semester."

Daniel Hastings

Signature/Advising Professor

Daniel Hastings, Class of 1956 Career Development Associate Professor of Aeronautics and Astronautics

TYPED NAME/TITLE OF ADVISING PROFESSOR

5025C

CONCURRENCE FORM

The Rome Air Development Laboratory requests the continuation of the AFOSR fellowship for Ms. Kristin Bennett, studying Computer Science at University of Wisconsin-Madison.

Give a brief statement of laboratory and/or Dr. N. Fowler (fellow's mentor) involvement with Ms. Kristin Bennett.

Ms. Bennett and her laboratory mentor, Dr. Northrup Fowler III, have established direct communications via electronic mail and an informal procedure whereby we quarterly exchange information on the status of our respective technology programs. We plan to have Ms. Bennett visit RADC next summer in connection with similar visits by other fellows for whom Dr. Fowler is laboratory mentor.

Fred I Diamond 31 Oct 89
Chief Scientist Date

Northrup Fowler III 27 Oct 89
Mentor Date

S-789-000-053

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Kristin Bennett

Semester/Academic Term: Summer/89

University: University of Wisconsin
Madison

Subcontract: S-789-000-053

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Name	Grade
Computer Science 990	Independent Study and Research	Satisfactory
Physical Education 132	Weight Conditioning	Satisfactory

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

See attached.

3. Give brief statement of your involvement with the Rome Air Development Laboratory and Dr. N. Fowler. Also list any items of interest such as academic awards, publications, other information that can be used for a LGFP newsletter.

Dr. Fowler and I have maintained informal contact with each other via electronic mail. Scheduling conflicts prevented me from making my introductory visit to the lab this summer. I look forward to visiting the lab and meeting Dr. Fowler in the near future.

"I certify that all information stated is correct and complete."

Signature/Fellowship Recipient

Kristin Bennett

TYPED NAME/FELLOWSHIP RECIPIENT

2202t

Research and Progress Towards Degree

This summer I investigated Nesterov's algorithm for smooth convex optimization problems. This algorithm has a rapid theoretical convergence rate. The algorithm parallelized with excellent efficiency and speed-up. The algorithm was tested on quadratic programs and linear programs. The linear programs were formulated as quadratic programs using the least-norm and proximal-point methods. Further theoretical and computational research is needed to fully access the usefulness of this approach. This fall, I am investigating applications of mathematical programming to questions in artificial intelligence. I'm interested in modeling neural network, machine learning, or pattern recognition problems as mathematical programming problems and applying optimization techniques to them. The area has good potential for a thesis topic.

My Master's degree will be completed by Christmas. I am preparing for my depth qualifying exam in February. I am making progress towards my degree.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Kristin P. Bennett is making satisfactory academic progress toward a Ph.D. in the area of Computer Science for the Summer 1989 academic term."

Olvi L. Mangasarian

Signature/Advising Professor

Professor Olvi L. Mangasarian

TYPED NAME/TITLE OF ADVISING PROFESSOR

2202t

CONCURRENCE FORM

The H.G. Armstrong Aerospace Medical Research Lab requests the continuation of the AFOSR fellowship for Ms. Leslie Brown, studying Electrical Engineering/Signal Processing at Leland Stanford, Jr. University.

Give a brief statement of laboratory and/or Dr. Richard L. McKinley (fellow's mentor) involvement with Ms. Leslie Brown.

Telephone conversations with Ms Brown and her faculty advisor indicate good progress toward her degree. Consideration of an adaptive signal processing algorithm for beam forming for her dissertation is underway. Ms Brown will visit the lab during this school year and is considering working in the lab ~~this~~ coming (1990) summer.

George C Mohr 16 Nov 89
Chief Scientist Date

Richard L McKinley 18 Oct 89
Mentor Date

RICHARD L. MCKINLEY
AAMRL/BBA
WPAFB OH 45433-6573

S-789-000-030

CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Ms. Leslie I. Brown

Quarter: Summer 1989

University: Stanford University

Subcontract: S-789-000-030

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

Course	Grade
Digital Signal Processing	A

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

Still working on Master's Degree.

"I certify that all information stated is correct and complete."

Leslie I. Brown

Signature/Fellowship Recipient

Leslie I. Brown

TYPED NAME/FELLOWSHIP RECIPIENT

LLD/sdp 5018C

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Ms. Leslie I. Brown is making satisfactory academic progress toward a Ph.D. in the area of Electrical Engineering/Signal Processing in the discipline of Electrical Engineering for the Summer 1989 quarter."

Signature/Advising Professor

Dwight G. Nishimura, Act Asst Prof.
TYPED NAME/TITLE OF ADVISING PROFESSOR

5018C

CONCURRENCE FORM

The Engineering and Service Center requests the continuation of the AFOSR fellowship for Mr. William Burkett, studying Civil Engineering at The University of Texas at Austin.

Give a brief statement of laboratory and/or Lt. James Underwood (fellow's mentor) involvement with Mr. William Burkett.

1. Mr. Burkett has been in frequent contact with our organization. The research he is proposing for his disertation will support current and future research projects at HQ AFESC/RDCS.

Michael D. Katona 14 Nov. 89 — J M Underwood 7 Nov 89

Chief Scientist Date — Mentor Date

S-789-000-059

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: William R. Burkett   Semester: Summer '89

University: Univ. of Texas at Austin   Subcontract: S-789-000-059

Fellow to complete:

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

ARE 383 - ADVANCED MASONRY DESIGN (B)
CE 397 - CIVIL ENGINEERING: STEEL STRUCTURES SEMINAR (CREDIT)
CE 397S - DISSERTATION RESEARCH (CREDIT)

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space if needed.)

Progress toward my dissertation was limited to discussion of possible topics. Discussions were held with several faculty members at the University of Texas at Austin during the summer. Additional discussions were held with government personnel at HQ Air Force Engineering and Services Center during my orientation visit in June '89. Possible topics include (but are not limited to):

- Modeling of Transfer Length for 0.6 Inch Prestressing Strand
- Analysis of Prestressed Concrete Box Girders Subjected to Blast Loadings
- Strengthening of Concrete Masonry Unit Walls for Out-of-Plane Loads

3. Give brief statement of your involvement with the Engineering and Services Center and Lt. James Underwood. Also include items of interest such as academic awards, publications, and other information that can be used for a LGFP newsletter.

My interaction with Lt. James Underwood occured during my orientation visit to HQ AFESC in June 1989 and included discussions of HQ AFESC interests as related to possible dissertation topics.

A large portion of my time this summer was used in completing a test program that I was involved in prior to being selected for the AFOSR-LGFP. Completion of the test program included publishing the following report:

Burkett, William R., and Frank, Karl H., Fatigue and Static Tests of 55-Strand Stay Cable Specimen for the Baytown Bridge, Test Report, Phil M. Ferguson Structural Engineering Laboratory, The University of Texas at Austin, August 1989.

"I certify that all information stated is correct and complete."

William R. Burkett 9/10/89
Signature/Fellowship Recipient

William R. Burkett

TYPED NAME/FELLOWSHIP RECIPIENT

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. William R. Burkett is making satisfactory academic progress toward a Ph.D. in the area of Civil Engineering for the Summer 1989 academic term."

James O. Jirsa

Signature/Advising Professor

James O. Jirsa, Professor

TYPED NAME/TITLE OF ADVISING PROFESSOR

2204t

CONCURRENCE FORM

The Armament Laboratory requests the continuation of the AFOSR fellowship for Mr. David Chenault, studying Physics at University of Alabama.

Give a brief statement of laboratory and/or Mr. Dennis Goldstein (fellow's mentor) involvement with Mr. David Chenault.

Mr Chenaults' activities at the University of Alabama in Huntsville (UAH) is an integral part of Mr Goldstein's research at the Armament Laboratory. The subject of both research activities is material properties measurements. Each organization has a highly specialized research instrument for making measurements. The UAH facility is making spectral measurements while the Armament Laboratory facility concentrates on specific wavelengths. One instrument is used to verify measurements made on the other. Error compensation equations developed at the Armament Laboratory have been given to UAH. Armament Laboratory samples will be loaned to UAH. Mr Chenaults' academic and research progress is being closely followed. Face-to-face technical interchange occurs monthly with more frequent telephone contact.

6/10/89

Chief Scientist Date

Dennis H. Goldstein 6 Oct 89

Mentor Date

S-789-000-060

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Mr. David Chenault Academic Term: Summer '89

University: Univ. of Alabama/Huntsville Subcontract: S-789-000-060

1. Courses - give description of courses and grades received.

PH 732 - Electricity and Magnetism II (text, Jackson)
Grade received: B
This course covered the second half of Jackson: wave guides, propagation of electromagnetic waves, scattering, relativity, and transformation of electric and magnetic fields.

2. Give a description of research and progress toward dissertation.

Data reduction on the infrared spectropolarimeter was developed to measure the linear retardance of samples. Data was taken on a CO_2 quarter wave retarder, achromatic quarter wave retarder, and a sample of liquid crystal. The Mueller matrix software was developed to produce Mueller matrix spectra uncorrected for deviations in azimuthal alignment of the polarization elements or variations in retardance for the quarter wave retarders. Work was begun on the software to correct for these problems.

3. Give a brief statement of your involvement with the Armament Laboratory and Mr. Dennis Goldstein. Also list any items of interest such as academic awards, publications, other information that can be used for a LGFP newsletter.

Cooperation with Mr. Goldstein and UAH included sharing of the algorithms for correction of azimuthal and retardance variations of the polarization elements. Mr. Goldstein's quarter wave retarders will be measured in the spectropolarimeter for calibration purposes before the start of the fall quarter.
I made a presentation at the SPIE annual meeting in San Diego, CA the first week in August on "Infrared Spectropolarimetry". The talk described the spectropolarimeter, the data reduction algorithms for various measurements, and the results of the retarder measurements. Two copies of the paper to be published in the conference proceedings are included.

"I certify that all information stated is correct and complete."

David Chenault
Signature/Fellowship Recipient

David Chenault

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. David Chenault is making satisfactory academic progress toward a Ph.D. in the area of Physics for the Summer 19 89 academic term."

Russell A Chipman

Signature/Advising Professor

Russell Chipman

TYPED NAME/TITLE OF ADVISING PROFESSOR

2094t

Infrared spectropolarimetry

David B. Chenault
Russell A. Chipman

University of Alabama in Huntsville
Huntsville, AL 35899

Abstract

This paper describes the infrared spectropolarimeter currently under development at the University of Alabama in Huntsville. The instrument, the data acquisition and processing algorithms, and several calibration issues are examined. Results are presented showing measurements of the retardance spectra of polarization elements, and the s- and p-transmission and diattenuation spectra of infrared coatings.

1 INTRODUCTION

The development of many infrared systems for optical computing, optical signal processing, optical interconnects, scene simulation, and neural networks is dependent on the spectral polarization characterization of polarization elements and spatial light modulator materials. The lack of data that has hampered efforts to improve infrared instrumentation has been widely documented[1]. The instrument and measurement techniques we have developed to address the need for spectral polarization data in the infrared should become essential tools in the development of electro- and magneto-optic materials and the calibration of polarization elements.

An infrared spectropolarimeter, a modified Fourier transform spectrometer, is ideally suited to measure the wavelength dependence of the polarization properties of potential modulator materials and polarization elements. The instrument is capable of measuring all sixteen elements of the Mueller matrix or specific polarization properties such as linear diattenuation and retardance of a sample. The Mueller matrix of the sample is calculated from at least sixteen spectra taken with the polarization elements of the polarimeter in a succession of orientations. A complete polarization characterization, including depolarization and scattering, as a function of wavelength of a potential modulator material may be determined in this manner. An incomplete polarization measurement, anything less than a complete Mueller matrix, or measurements of specific polarization properties[2] are measured with less complicated configurations of the polarimeter in the sample compartment. These configurations are useful for determining the spectral response of a polarizer or retarder, or determining the wavelength dependence of the dichroism of a retarder or the birefringence of a polarizer.

Previous investigations have measured the Mueller matrix samples at laser wavelengths[3], or measured incomplete polarization characteristics as a function of wavelength[4,5,6]. Since laser wavelengths occur only coincidentally near absorption bands for a particular material, data on the many interesting physical phenomena that occur near these spectral regions are inaccessible to laser polarimeters. The spectral capability of the spectropolarimeter allows the polarization properties of the sample in all wavelength regions in the mid-infrared to be investigated simultaneously.

2 THE SPECTROPOLARIMETER

The spectropolarimeter is a Fourier transform spectrometer modified by the insertion of a polarimeter in the sample compartment (Figure 1). The spectrometer is operated in the normal spectrometer fashion for one orientation of the elements in the polarimeter. A series of spectra are taken in this fashion for different orientations of the polarimeter elements. These spectra are reduced to produce spectra of a Mueller matrix or a specific polarization property. The exact polarimeter configuration and number of measurements depends on the completeness of the polarization measurement desired, i.e. sixteen measurements for a Mueller matrix or nine measurements to find linear diattenuation and retardance. The polarimeter configurations and data reduction are described in detail in Section 3.

The spectrometer has a spectral range of 2.5 to 25μm. The broad spectral range of the polarization measurements places restrictions on the polarization elements. The polarizers and retarders in the polarimeter should have nearly achromatic response. Commercially available polarizers achieve the required performance. We use wire grid polarizers that transmit 80% of plane polarized light from 2.5 to 24μm and have an extinction ratio of approximately 100 over the same range.

The achromatic restriction on the quarter wave retarders required for measuring Mueller matrices is more stringent. Conventional wave plates, consisting of a single plate of birefringent material, are extremely wavelength dependent; the retardance takes on values of $2n\pi$ a number of times over this wavelength region. Modified Fresnel rhombs have the required performance but are large, long, and expensive. Our solution was to design a wave plate combination of two different materials with similar birefringence and dispersion. The two plates produce a net birefringence of approximately one quarter wave (±15°) from 2.5 to 14μm.

With these specifications, the spectropolarimeter can measure linear diattenuation and linear retardance from 2.5 to

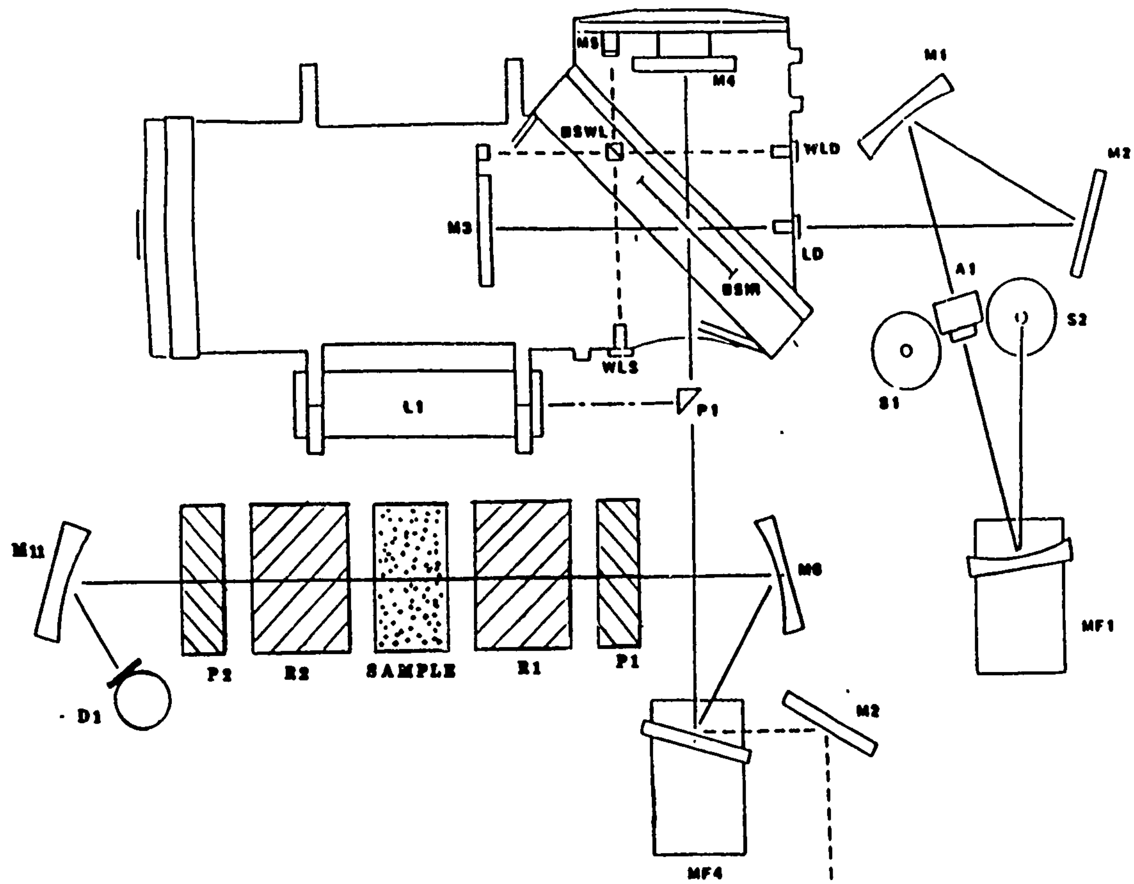

Figure 1: The Fourier transform infrared spectropolarimeter. The Mueller matrix polarimeter configuration is shown in the sample compartment.

24μm. The Mueller matrix, circular diattenuation, and circular retardance of samples may be measured over the range of achromaticity of the retarders, from 2.5 to 14μm.

3 DATA ACQUISITION AND PROCESSING

3.1 Mueller matrix

The Mueller matrix provides the most complete polarization information about a sample and requires the most sophisticated polarimeter configuration and data reduction techniques. Mueller matrix polarimeters are described in the literature[7,8]; we have followed the prescription given by Azzam.

Our Mueller matrix polarimeter (Figure 1) consists of a fixed polarizer, a rotating quarter wave retarder, the sample, a second rotating quarter wave retarder, and a second fixed polarizer, the second retarder rotating at five times the rate of the first. The Mueller matrix of the system, M_{sys}, is given by

$$M_{sys}(\lambda,\theta_1,\theta_2)=M_{P2}(\lambda)M_{R2}(\lambda,\theta_2)M_S(\lambda)M_{R1}(\lambda,\theta_1)M_{P1}(\lambda) \quad (1)$$

where the subscripts refer to the second polarizer P2, second retarder R2, the sample S, the first retarder R1, and first polarizer P1. The retarders are rotated in discrete steps with transmission spectra taken between each rotation. The output intensity resulting from the rotation of the retarders is

$$I(\lambda,\theta_1,\theta_2)=\sum_{i=1}^{4} M_{1i}\vec{S}_i \quad (2)$$

where M_{1i} is the top row of the system Mueller matrix M_{sys}. The intensity modulation may be expressed as a Fourier series

$$I(\lambda,\phi)=a_0+\sum_n (a_n\cos n\phi+b_n\sin n\phi) \quad (3)$$

The Mueller matrix elements of the sample, M_S, are recovered from the coefficients of the series in the manner described by Azzam and Hauge. The Mueller matrix elements are encoded on the even frequencies of the Fourier series. The odd frequencies, however, contain useful information on the beam wander caused by rotating polarization elements.

There are many advantages to finding the Mueller matrix in this manner. With the spectropolarimeter all wavelengths are investigated simultaneously rather than one at a time as in laser polarimeters. The spectral Mueller matrix provides complete polarization information of the sample including depolarization and scattering. These features of spectropolarimetric measurements will enhance the development of current modulators in the mid-infrared the discovery of new modulator materials.

3.2 Diattenuation of an interface at nonnormal incidence

3.2.1 Theory

Diattenuation measurements in transmission of an optical window are made with a simpler configuration of the sample compartment. The diattenuation of the sample is the property of having polarization dependent transmission. Linear diattenuation is defined by

$$D(\lambda,i)=\frac{I_s(\lambda,i)-I_p(\lambda,i)}{I_s(\lambda,i)+I_p(\lambda,i)} \tag{4}$$

where i is the angle of incidence, and s and p are the polarization states perpendicular and parallel to the plane of incidence respectively. D varies from 0 to 1 where 0 is unpolarizing and 1 is completely polarizing.

The sample is positioned on a rotary stage between two polarizers so that the angle of incidence may be varied from 0° to 90° (Figure 2). A series of spectra are taken with the polarizers oriented to measure the s- and p- polarization states of the sample. These spectra are then reduced using (eq. 4).

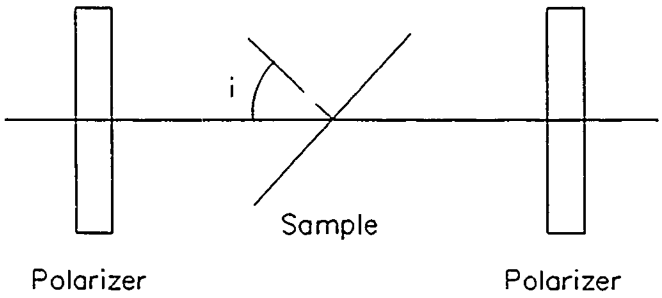

Figure 2: The polarimeter configuration for measuring an interface at nonnormal incidence.

3.2.2 Results

This technique was used to find the diattenuation of an infrared band pass filter. Figure 3 shows the transmittance of the filter at normal incidence, 40° and 70° incidence. The diattenuation arises from the difference in the s- and p- states for a given angle of incidence and is shown in Figure 4.

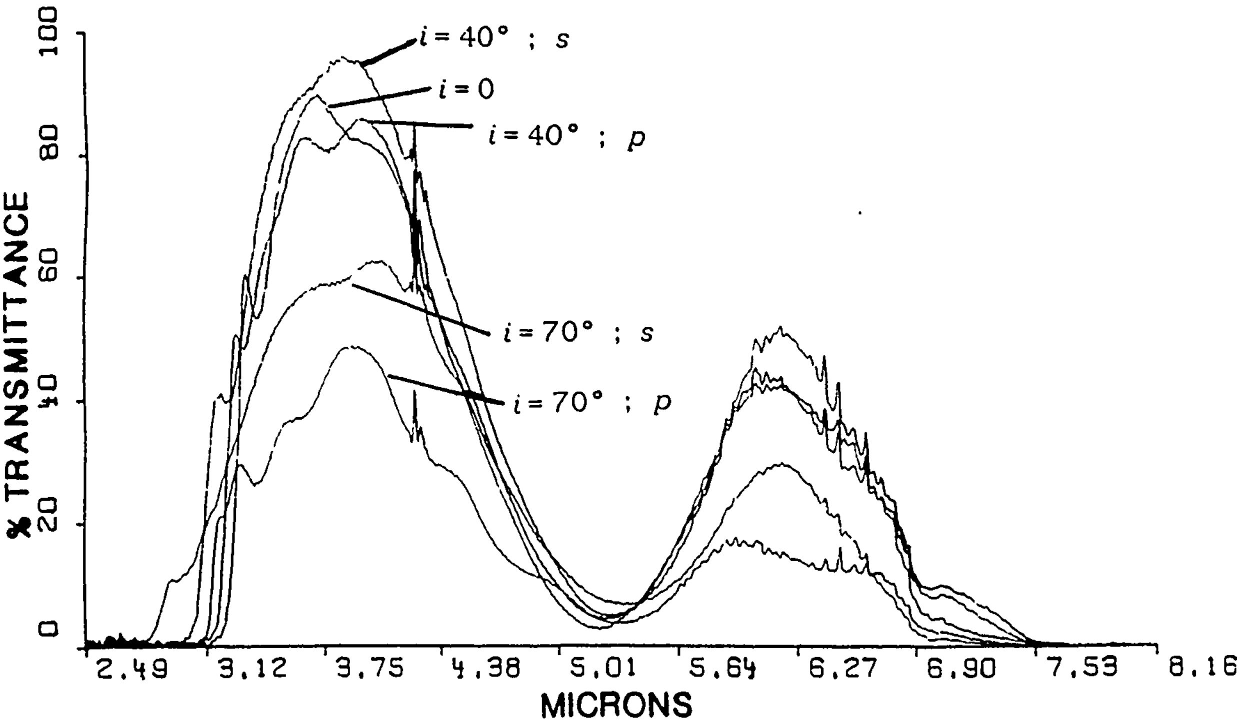

Figure 3: Transmission of s- and p- states at 0°, 40°, and 70° angles of incidence of an infrared band pass filter.

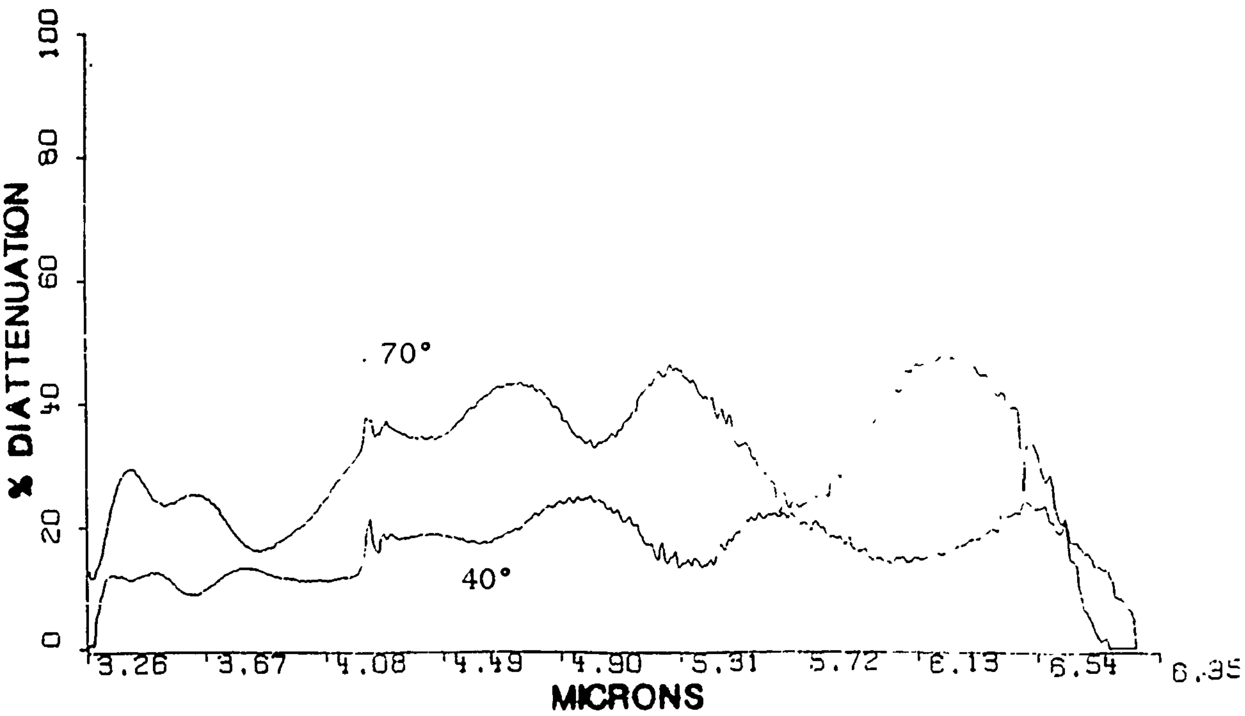

Figure 4: The diattenuation of the filter at 40° and 70°.

3.3 Linear diattenuation and retardation

3.3.1 Theory

Linear diattenuation and retardation of a sample are determined with the polarimeter configuration shown in Figure 5. The sample is placed between two fixed polarizers and rotated in discrete steps. The output intensity modulation is analyzed through Fourier analysis as described in section 3.1. In this instance the linear diattenuation is encoded on the second harmonic of the Fourier series (eq. 3) and the linear retardance on the fourth harmonic. The retardance is recovered from the coefficients by

$$\delta(\lambda) = 2\cos^{-1}\sqrt{\frac{a_0(\lambda)-c(\lambda)}{a_0(\lambda)+c(\lambda)}} \tag{5}$$

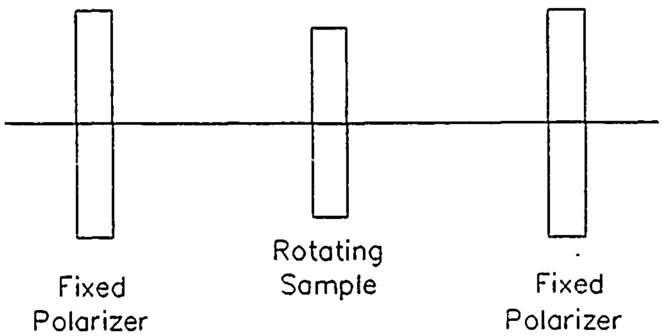

Figure 5: The polarimeter configuration for determining linear diattenuation and retardance of the sample.

This measurement process provides a means of calibration of the spectral response of polarization elements. These calibration spectra are necessary for the development of future polarimeters and other infrared systems.

3.3.2 Results

Figure 6 shows the fourth harmonic coefficients, a_4 and b_4, and the dc term a_0 of an infrared achromatic retarder. Figure 7 is the retardance spectrum calculated from (eq. 5). The retardance of the compound wave plate varies within $\pm 15°$ of one quarter wave.

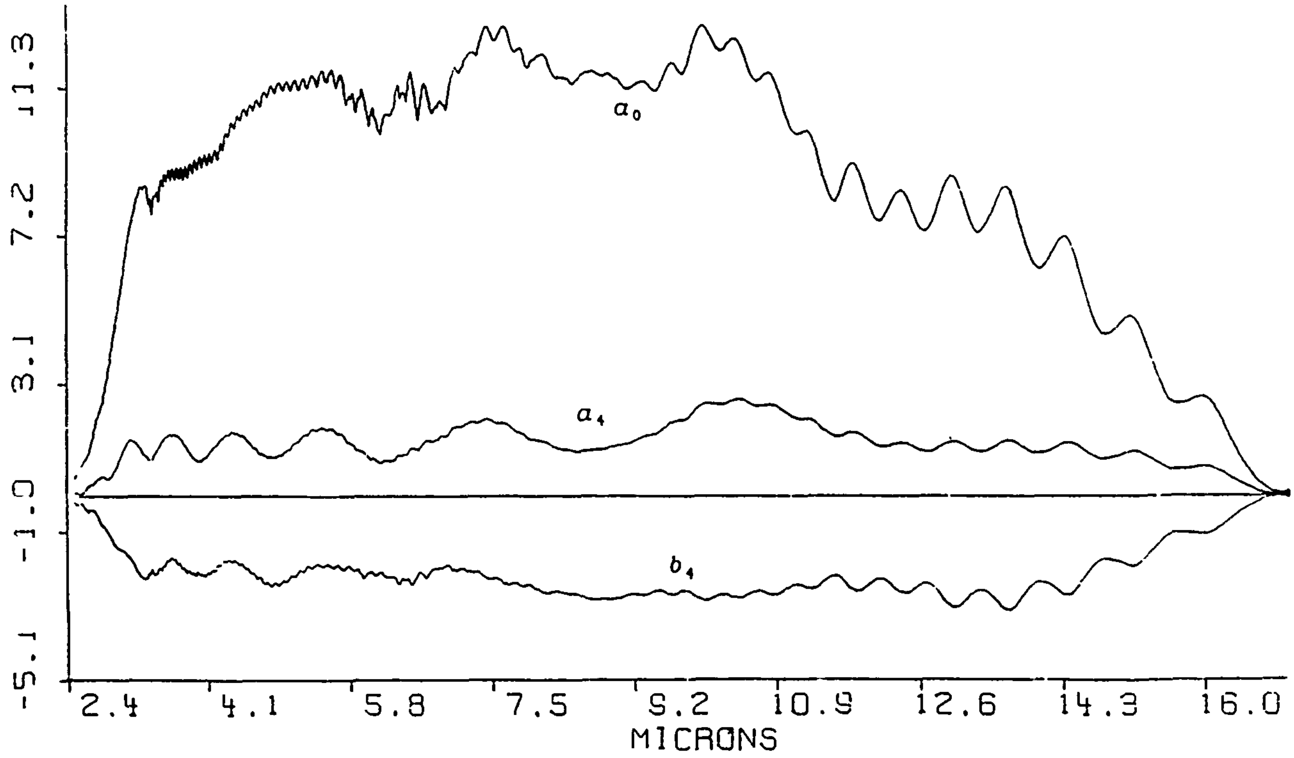

Figure 6: Fourth harmonic coefficients, a_4 and b_4, and the dc term a_0 of the Fourier expansion of the intensity modulation due to the rotation of the wave plate.

The retarders used in the spectropolarimeter and investigated here were designed to have a retardance of 90°±3°. The deviation of the experimental results from design may be due to misalignment of the fast axes, misalignment of the crystal axes, coating and surface imperfections, or thickness errors. The discrepancy between experimental and design results underscores the need for an instrument that is capable of measuring such defects and making calibration measurements.

We have also investigated the infrared polarization characteristics of a liquid crystal sample. Figure 8 shows the transmission of a liquid crystal sample 50μm thick sandwiched between CaF_2 windows. Figure 9 shows the retardance spectrum over the same wavelength range. Measurements on similar materials will facilitate the development of spatial light modulators.

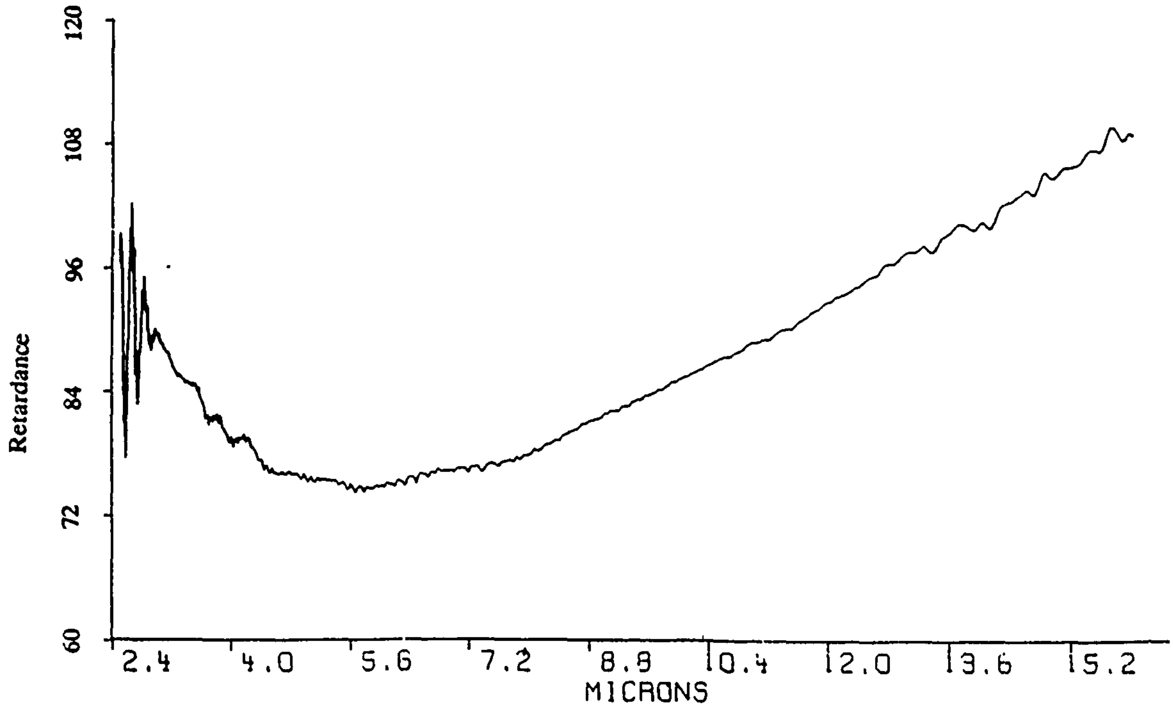

Figure 7: The retardance spectrum of the achromatic wave plate.

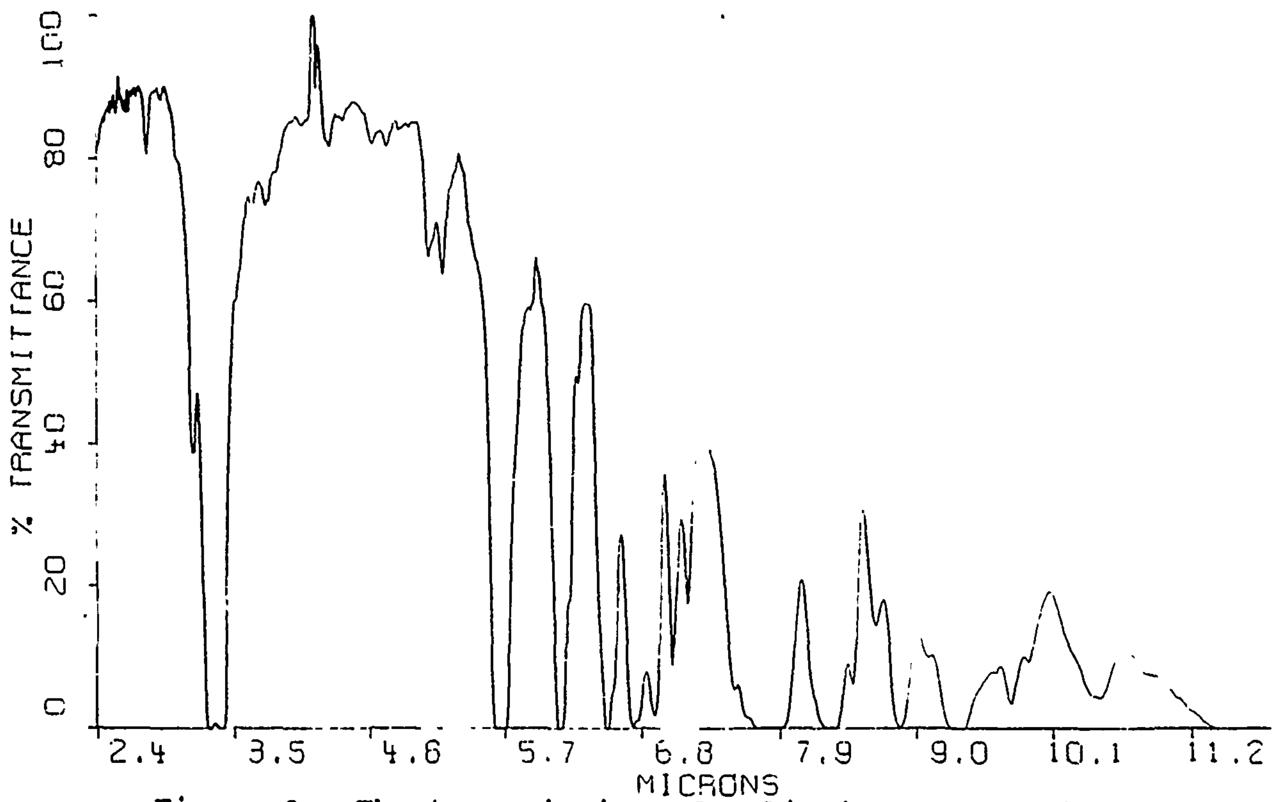

Figure 8: The transmission of a liquid crystal with CaF_2 windows.

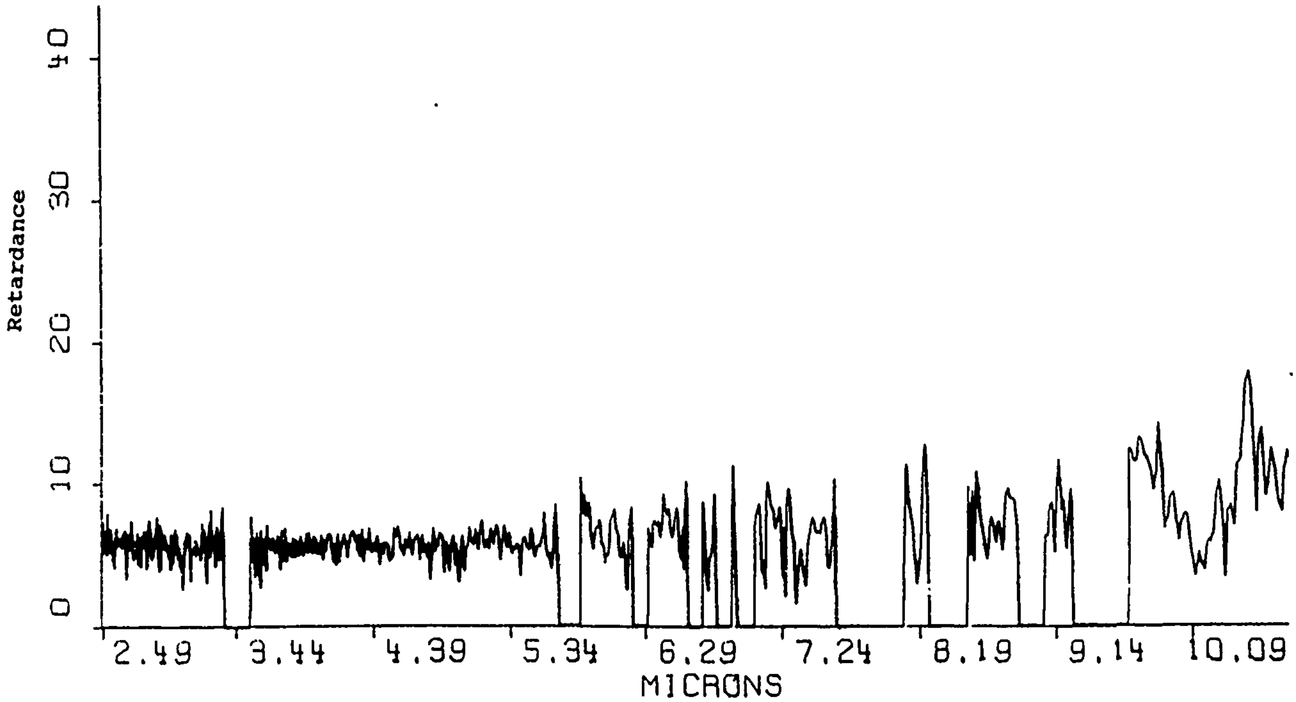

Figure 9: The retardance spectrum of the liquid crystal. The units on the y-axis are degrees.

4 CALIBRATION ISSUES

The ability of the spectropolarimeter to make extensive polarization measurements is dependent on the resolution of complex calibration issues. Most of the calibration problems stem from the non ideal aspects of polarization elements and the spectral nature of the measurements. The wavelength dependence of the polarization elements, for example the variation of retardance in the quarter wave retarders, requires calibration spectra that must be included in data reduction[9]. Instrumental polarization, which is also wavelength dependent, must be accounted for in measurements where the polarization states entering and leaving the sample compartment are not constant, for example the diattenuation measurements of section 3.2.

Additional problems arise in determining the exact azimuthal orientation of the polarization elements. It has been shown[10] that misalignments of the fast axis of the retarders in the Mueller matrix configuration can lead to large errors in the final output Mueller matrix. There are several solutions to this problem. One method utilizes the phase information of Fourier analysis to determine the exact orientation of the transmission axis of a polarizer or fast axis of a retarder. An alternate solution is to perform a least squares fit of a known Mueller matrix (i.e. the identity matrix for no sample) to determine the orientation of the polarization elements. Both solutions are difficult and time consuming.

In optical systems where radiometric measurements are made, rotating elements whose surfaces are not plane parallel cause beam wander. The intensity variations due to beam wander can be disastrous in polarimetric measurements where variations can be misinterpreted as polarization. A detector array should alleviate this problem.

5 SUMMARY

Spectropolarimetry is a means of adding a large knowledge base to what is known about the polarization properties of materials. The ability of the spectropolarimeter to measure the Mueller matrix as a continuous function of wavelength over the entire mid-infrared will enhance and facilitate the development of infrared systems. Calibration of retarders and the importance of this calibration has been demonstrated. The spectropolarimeter described here should become an essential tool in the development of spatial light modulators both for the development of modulator materials and the calibration of these devices.

6 ACKNOWLEDGEMENTS

This work was sponsored in part by the Laboratory Graduate Fellowship Program through Universal Energy Systems and the Air Force Office of Scientific Research, contract #F49620-86-C-0127/SB5861-0436. The authors wish to thank Dennis Goldstein and Dorothy Sauer for their helpful discussions.

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3. R. M. A. Azzam, "Photopolarimetric measurement of the Mueller matrix by Fourier analysis of a single detected signal", Opt. Lett. 2, 6 (1978).

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8. P. S. Hauge, "Mueller matrix ellipsometry with imperfect compensators", J. Opt. Soc. Am. 68 (11), 1519-1528 (1978).

9. D. H. Goldstein and R. A. Chipman, "An Error Analysis of a Mueller Matrix Polarimeter", submitted to J. Opt. Soc. Am. (1989).

10. D. H. Goldstein and R. A. Chipman, "An Error Analysis of a Mueller Matrix Polarimeter", submitted to J. Opt. Soc. Am. (1989).

CONCURRENCE FORM

The Avionics Laboratory requests the continuation of the AFOSR fellowship for Mr. Curt Richter, studying Applied Physics at Yale University.

Give a brief statement of laboratory and/or Major Ken Soda (fellow's mentor) involvement with Mr Curt Richter.

Due to academic commitments over the Summer of 1989, Mr Richter was unable to complete his Lab Graduate Fellowship orientation visit to the Wright Research and Development Center until late September. During this visit, Mr Richter presented Lt Col Soda and several other members of the professional staff with a detailed description of longitudinal quantization effects in the quantum Hall regime which are under study by his research group at Yale. His presentation was very well received and spawned several technical exchanges.

Lt Col Soda provided a tour of both the Electronic Technology Laboratory and parts of the Materials Laboratory. He also discussed at length the capabilities and interests of these organizations. Also discussed were potential for epitaxial semiconductor material growth, photolithographic processing support and a period of on-site research which WRDC may be able to provide Mr Richter as his academic program continues. Although Mr Richter's exact thesis research has yet to be finalized, this exchange was highly informative and served as a basis for future interaction.

Edwin B. Champagne 17 Oct 1989

Chief Scientist Date
EDWIN B. CHAMPAGNE
Acting Chief Scientist
Electronic Technology Laboratory
S-789-000-073

Kenneth J. Soda

Mentor Date
KENNETH J. SODA, Lt Col, USAF
Ch, Characterization & Analysis Br
Research Division

Certification Needed for Each Academic Term
CERTIFICATION OF ACADEMIC PROGRESS

Fellow: Curt A. Richter | Semester/Academic Term: Summer 1989

University: Yale University | Subcontract: S-789-000-073

Fellow to complete

1. Courses - Give description of courses and grades received. (Attach sheet if extra space is needed.)

   No courses taken

2. Give a description of research and progress toward dissertation. (Attach sheets if extra space is needed.)

   see attached sheets

3. Give brief statement of your involvement with the Avionics Laboratory and Major Ken Soda. Also include items of interest such as academic awards, publications, and other information that can be used for a program newsletter.

   I have contacted Major Soda and discussed areas of mutual interest. We arranged my orientation visit for late September 1989.

"I certify that all information stated is correct and complete."

Curt A. Richter
Signature/Fellowship Recipient

Curt A. Richter
TYPED NAME/FELLOWSHIP RECIPIENT

2200t

2: Description of research and progress

I spent the summer of 1989 at Yale University working in the laboratory with Professor R. G. Wheeler. The fabrication of a He^3 cryostat, that was begun in the spring, was completed. I performed research on electron transport in the Quantum Hall regime. These experiments involved the fabrication of devices (down to 5μm in size) from GaAs/AlGaAS heterostucture wafers, and measuring the electron transport properties in these devices at low temperatures (0.4 - 4.2K) and high magnetic fields (0 - 7 Tesla). I studied both the effects of probe size on the Quantum Hall Effect and quantization of the longitudinal resistance in the Quantum Hall Regime.

CERTIFICATION OF ACADEMIC PROGRESS

"I certify that Mr. Curt A. Richter is making satisfactory academic progress toward a Ph.D. in the area of Applied Physics for the Summer term."
1989

Signature/Advising Professor

Robert G. Wheeler, Professor of Applied Physics
TYPED NAME/TITLE OF ADVISING PROFESSOR

2200t